Edward Jacobi
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MOLYBDENUM, CERIUM AND RELATED ALLOY STEELS

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GENERAL INTRODUCTION

American Chemical Society Series of Scientific and Technologic Monographs

By arrangement with the Interallied Conference of Pure and Applied Chemistry, which met in London and Brussels in July, 1919, the American Chemical Society was to undertake the production and publication of Scientific and Technologic Monographs on chemical subjects. At the same time it was agreed that the National Research Council, in coöperation with the American Chemical Society and the American Physical Society, should undertake the production and publication of Critical Tables of Chemical and Physical Constants. The American Chemical Society and the National Research Council mutually agreed to care for these two fields of chemical development. The American Chemical Society named as Trustees, to make the necessary arrangements for the publication of the monographs, Charles L. Parsons, Secretary of the American Chemical Society, Washington, D. C.; John E. Teeple, Treasurer of the American Chemical Society, New York City; and Professor Gellert Alleman of Swarthmore College. The Trustees have arranged for the publication of the American Chemical Society series of (a) Scientific and (b) Technologic Monographs by the Chemical Catalog Company of New York City.

The Council, acting through the Committee on National Policy of the American Chemical Society, appointed the editors, named at the close of this introduction, to have charge of securing authors, and of considering critically the manuscripts prepared. The editors of each series will endeavor to select topics which are of current interest and authors who are recognized as authorities in their respective fields. The list of monographs thus far secured appears in the publisher's own announcement elsewhere in this volume.

The development of knowledge in all branches of science, and especially in chemistry, has been so rapid during the last fifty years and the fields covered by this development have been so varied that it is difficult for any individual to keep in touch with the progress in branches of science outside his own specialty. In spite of the facilities for the examination of the literature given by Chemical Abstracts and such compendia as Beilstein's Handbuch der Organischen Chemie, Richter's Lexikon, Ostwald's Lehrbuch der Allgemeinen Chemie, Abegg's and Gmelin-Kraut's Handbuch der Anorganischen Chemie and the English and French Dictionaries of Chemistry, it often takes a great deal of time to coördinate the knowledge available upon a single topic. Consequently when men who have spent years in the study of important subjects are willing to coördinate their knowledge and present it in concise, readable form, they perform a service of the highest value to their fellow chemists.

It was with a clear recognition of the usefulness of reviews of this character that a Committee of the American Chemical Society recommended the publication of the two series of monographs under the auspices of the Society.

Two rather distinct purposes are to be served by these monographs. The first purpose, whose fulfilment will probably render to chemists in general the most important service, is to present the knowledge available upon the chosen topic in a readable form, intelligible to those whose activities may be along a wholly different line. Many chemists fail to realize how closely their investigations may be connected with other work which on the surface appears far afield from their own. These monographs will enable such men to form closer contact with the work of chemists in other lines of research. The second purpose is to promote research in the branch of science covered by the monograph, by furnishing a well digested survey of the progress already made in that field and by pointing out directions in which investigation needs to be extended. To facilitate the attainment of this purpose, it is intended to include extended references to the literature, which will enable anyone interested to follow up the subject in more detail. If the literature is so voluminous that a complete bibliography is impracticable, a critical selection will be made of those papers which are most important.

The publication of these books marks a distinct departure in the policy of the American Chemical Society inasmuch as it is a serious attempt to found an American chemical literature without primary regard to commercial considerations. The success of the venture will depend in large part upon the measure of coöperation which can be secured in the preparation of books dealing adequately with topics of general interest; it is earnestly hoped, therefore, that every member of the various organizations in the chemical and allied industries will recognize the importance of the enterprise and take sufficient interest to justify it.

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DEDICATION

To Dr. C. L. Parsons and Dr. R. B. Moore, former successive Chief Chemists of the United States Bureau of Mines, whose broad vision, sound common-sense, and scientific knowledge have been an inspiration and whose kindly encouragement has been a help, this book is affectionately dedicated.

H. W. G.
E. L. M.

Preface.

This book is based on the thesis that a given alloy steel is a member of a class rather than a special entity and that with due regard to required heat-treatment it is often possible to produce, by combination or substitution of alloying elements, several chemically different steels which are practically interchangeable for the same engineering application.

This idea has guided many metallurgists in recent years and has been emphasized well by Aitchison in his "Engineering Steels." Aitchison, however, has confined that book to the alloy steels universally available to the engineer. American conditions make it desirable that molybdenum steel also be discussed from this point of view. The United States has large reserve supplies of molybdenum while the domestic supply of many of the other alloying elements is restricted, either by Nature or by economic conditions. Molybdenum is now known to be one of the most potent alloying elements for steel. American steel makers know how to make molybdenum steel, and have made it readily obtainable in the American market.

Molybdenum is destined to take its place beside nickel, chromium and vanadium as an alloying element. Before it can take and hold that place, its possibilities and limitations must be better understood, and it is for this better understanding that this book is written. The largest gaps in the knowledge of molybdenum steel seem to be its effect on the endurance and impact properties, and its effect on the properties of "transverse" specimens. The experimental work herein recorded was planned with a view to filling those gaps.

Since the experimental work on both molybdenum and cerium was carried on together, the title has been chosen to express this fact at the risk of erroneously seeming to class cerium as necessarily a true or a useful alloying element.

Acknowledgments.

Under instructions from the Director of the Bureau of Mines the authors have written this book as part of their official duties. This method of publication is adopted as the best available one for placing the results of the work in the hands of interested metallurgists, with reasonable promptness. The authors are receiving no royalties from the publication.

Thanks are due Mr. G. L. Norris, of the Vanadium Corporation of America, and to Dr. H. S. Miner, of the Welsbach Company, for enlisting the coöperation of those firms in the experimental work.

The courtesy of Mr. J. H. Nelson, of the Wyman-Gordon Company, in making Stanton and Izod tests; that of Prof. H. Diederichs of Sibley College, Cornell University, in granting facilities for making endurance tests; the aid of Mr. R. J. Thompson, formerly of the Vanadium Corporation; and of Messrs. W. B. Smith and V. H. Schnee, formerly of the Welsbach Company, in the experimental work, is gratefully acknowledged.

The chapter on molybdenum in nickel-silicon steel is based on coöperative work with the Navy Department, much of the test data having been kindly supplied by Mr. Jerome Strauss of the Naval Gun Factory. Some of the data on molybdenum in nickel steels have been furnished by Mr. C. McKnight, Jr., formerly of the Carbon Steel Company. To these, and to a number of metallurgists who have read and criticised the manuscript, thanks are due.

The interest of Professor G. B. Upton, of Sibley College of Engineering at Cornell University, has been a help during the prosecution of this work.

In common with all who carry out endurance tests, the authors owe a debt of gratitude to Professor H. F. Moore, of the University of Illinois, Engineering Experiment Station, for the enlightenment afforded by his epoch-making investigations into phenomena connected with the fatigue failure of metals. We are further indebted to Professor Moore for his critical study of the endurance data contained herein.

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MOLYBDENUM, CERIUM AND RELATED ALLOY STEELS

Chapter 1.

The Effect of Alloying Elements as a Class.

The Limitations of Carbon Steel. Pure iron is soft and ductile. It is classed with steel because of its chemistry rather than its strength. If no combination with iron were possible, the ferrous alloys would not have their dominant position and our minds would not make the automatic distinction between ferrous alloys as rather hard and rather strong, and non-ferrous as rather soft and weak.

The addition of carbon to iron gives steel, "a malleable alloy of iron and iron carbide."[1]

With the introduction of carbon the strength and hardness in the cast or rolled state increases, and with sufficient carbon there enters the possibility of heat-treatment, *i.e.*, control of the size and distribution of the particles of iron carbide in the ferrite through suitable temperature changes. But when we try to obtain the greatest possible strength in steel we find that the very strongest carbon steels, made so by high carbon content or by heat-treatment, tend to be brittle and lacking in toughness.

Carbon steel, below the brittle limit, is good or bad according to the care taken in its manufacture and in its heat-treatment. When the engineering requirements are not too severe carbon steel is adequate. When greater strength and toughness are needed, it may become either impossible to attain the desired results or too costly to exert the care in steel-making and in heat-treatment required to get a uniform and trustworthy product of the desired properties. For producing greater intrinsic strength and toughness and better uniformity, the use of deoxidizing and scavenging elements is of some avail, and the possibilities in properly made and scavenged, properly heat-treated carbon steel have not yet been exhausted. But the possible limit, and especially the practical limit, is not high enough for the present demands of the engineer.

The old struggle between projectile and armor for the Navy, and, more recently, the development of the automobile and aircraft have

[1] References are given in Appendix E, p. 282.

called for the production of steels of higher and higher mechanical properties. The need is met by alloy steels.

An alloy steel is, broadly, one in which properties not attainable, or attainable with difficulty, in carbon steel are secured or more readily secured by the addition of some other element or elements. The alloying elements strengthen the steel.

Fortunately, the effects of different alloying elements are usually shown in the presence of each other, so that the benefits derived from one may be added to those from another. Few of the elements are incompatible. Some elements even seem to accentuate the effect of others so that a little of one element plus a little of another will have a greater effect than a much larger quantity of one element alone.

The comparison of alloy steels is made complex by the fact that no single property tells the whole story. Among steels similarly handled, *i.e.,* by rolling and normalizing, by annealing, or by quenching and tempering, strength and ductility are inversely connected, the stronger steels being the more brittle and the weaker the more ductile. In some cases the maximum strength is the property most desired.

When great ability to resist static distortion is required the proportional limit is the property of greatest interest. When a machine part must resist repeated stress, the endurance limit is the most important one. If the design of the part calls for sharp changes of section or notches, like a screw thread, and the part may be subject to sudden blows, the ability to withstand impact is of importance.

Some of these properties are inter-related, but seldom by straight-line relations. In going from the hard to the soft state in a given steel, the ductility and the resistance to impact increase more readily on the soft end of the curve; but on the very hard end, say above 200,000 pounds/square inch tensile strength, these properties may increase instead of continuing to decrease.

The elastic limit may lie at 50 per cent. of the tensile strength or at 95 per cent. The endurance limit is roughly proportional to the tensile strength, but may vary considerably. Fig. 1 (after Hatfield [277]) shows how complex are the relationships among the various properties in a typical alloy steel.

Inasmuch as the tensile strength is generally determined when any other property of a steel is determined, and hence carries a general connotation in the mind of the engineer as to the probable corresponding range of compression, torsion and shear strengths, ductility, elastic limit, endurance limit and impact resistance, it is most convenient to compare the other mechanical properties of steels on the basis of equal tensile strengths. Another advantage of using the tensile strength as the basis of comparison lies in the fact that the Brinell hardness is almost directly

proportional to the tensile strength. The Brinell hardness test is easily and quickly made and may be applied to most finished parts without damage.

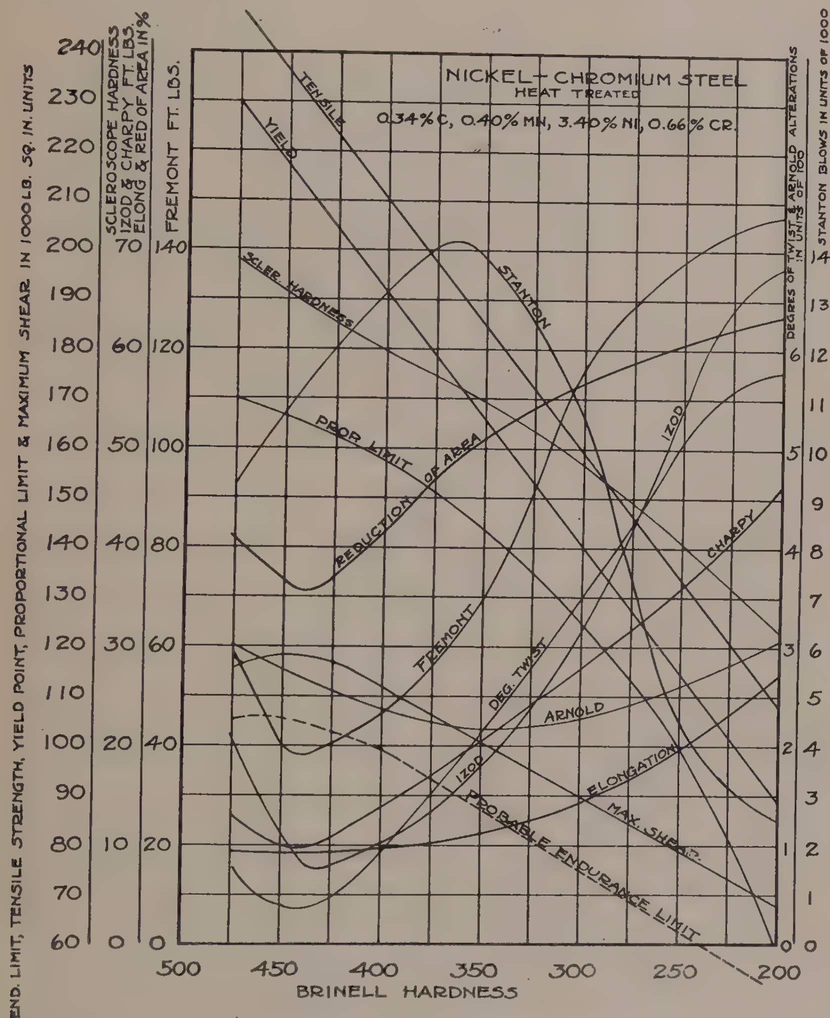


FIG. 1.—Curves showing inter-relation of the various mechanical properties of a heat-treated alloy steel.

For a given tensile strength the alloy steels show higher proportional limit, greater ductility and impact strength, but about the same endurance limit as the carbon steels. It is especially noticeable that to secure high tensile strength, the carbon steels demand high carbon content, quenching in water or brine and a low draw temperature. The introduction of

alloying elements gives the strength at lower carbon content, with oil or air quenching and with very much higher draw temperatures.

Fundamentals of the Heat-Treatment of Carbon Steel. In the following pages alloy steels will be considered primarily from the point of view of the automotive engineer and no attempt will be made to discuss high speed tool steels or other steels outside of the classes used in automotive construction.

Attention will be centered on hypoeutectoid alloy steels which are to be used in the heat-treated condition. The term heat-treatment will be used herein to refer to the process of hardening by quenching (in water, oil or air) followed by a re-heating, tempering or drawing process. The processes of annealing or normalizing will be referred to by those terms and not by the term heat-treatment.

The composition and the heat-treatment of an alloy steel are factors which are necessarily inter-related. To produce a definite set of properties the heat-treatment must be adapted to the composition.

The composition has a great effect on the possibilities for development of properties through heat-treatment and on the ease of heat-treatment. The alloying elements may be classified with respect to their effect on susceptibility of steel to heat-treatment.

Before developing such a classification, the heat-treatment of hypoeutectoid carbon steel may be briefly reviewed.

Starting with an annealed 0.45 per cent steel, made up of ferrite (α iron) and pearlite (the latter being an intimate eutectoid mixture of ferrite and the carbide of iron known as cementite, Fe_3C), the steel is originally soft. On heating to about 740° C. (1360° F.) the pearlite changes into austenite. The α iron of pearlite, in which Fe_3C is insoluble, goes over to γ iron, in which Fe_3C is soluble, so that the pearlite is now replaced by austenite containing in solid solution the eutectoid percentage of carbon. Fe_3C probably breaks down into $Fe + C$ so that in austenite the carbon is probably in solution as such instead of as Fe_3C. For present purposes it is immaterial in which form the carbon exists in austenite. This inversion is the Ac_1 change. As the temperature is raised the free α iron of the original steel progressively goes over to γ iron (Ac_3 change). Since the γ iron can dissolve carbon, a diffusion of carbon progressively takes place from the carbon-rich γ first formed into the γ formed later. This diffusion requires time and its rate is dependent on the amount by which the Ac_3 temperature is exceeded. The complete homogeneity of the austenite is of prime importance in heat-treatment. The more homogeneous is the austenite, the more effective is quenching in producing hardness. By raising the temperature very greatly, even steel with less than 0.10 per cent carbon may be materially hardened.(2)

Giolitti (3) strongly emphasizes the necessity for homogeneity of aus-

tenite. Howe and co-workers [4] also point it out. A small piece of carbon steel "flashed" to a high temperature for a very short time before quenching will show mechanical properties much higher than the same steel raised just above the Ac_3 point. But in carbon steel there is a very great tendency for grain growth in austenite. This gives rise to coarse aggregates of martensite on quenching and consequent brittleness in the steel. Consequently, with carbon steels one cannot take advantage of the benefits of a complete homogenizing of the austenite. Writers on heat-treatment of carbon steel commonly use italics [5, p. 71; 6, p. 274] [a] in discussing this point to emphasize that the lowest possible quenching temperatures must be used in practice.

Some alloying elements greatly reduce the tendency toward grain growth in austenite and hence allow the use of high temperatures and long heating before quenching. Not only does such use allow uniform diffusion of carbon, but also of the alloying element.

Nickel has a decided effect in raising the allowable temperature of heating before quenching, while chromium has the opposite effect. Straight chromium and straight manganese steels have even less leeway in temperature than carbon steels. In nickel chromium steels, with common ratios of nickel to chromium, the favorable influence of nickel overbalances the unfavorable influence of chromium on this score.[5, p. 308]

Vanadium acts like nickel in this respect. Plain vanadium and chromium-vanadium steels give best results with quenching temperatures that would be abnormally high for carbon steels of similar carbon content.

Some alloying elements thus give leeway in maximum temperature. Alloying elements may also affect the eutectoid percentage of carbon, usually lowering it. Thus the carbon content of the austenite first formed is lower, with the result that less carbon diffusion is required to produce a homogeneous austenite. This means that either a lower temperature or a shorter time will suffice than would be the case in the absence of the alloying element.

Some of the alloying elements raise and some lower the temperature of the inversion on heating. Since the end of the Ac_3 range must be exceeded in forging, or in heating before quenching, the location of this temperature of complete conversion to austenite is of fundamental importance.[7]

Now consider the behavior of austenite on cooling. Its behavior is controlled by the rate of cooling. If this be extremely slow as when the steel is allowed to cool down in the furnace, changes take place which are the exact reverse of those occurring during heating. The austenite goes over into ferrite and pearlite, *i.e.*, into the stable constituents and no hardening results. This reverse change takes place at slightly lower

[a] Page numbers thus given refer to pages in the references cited.

temperature than it did on heating, but it is the same change. Increase in maximum temperature, in carbon content, or moderate increase in rate of cooling may still further lower the temperature of the change.

But this inversion, like other physico-chemical changes of similar nature, can be suppressed by extremely rapid cooling; *i.e.*, the steel may be undercooled. In the extreme case the inversion can be entirely suppressed and the steel will remain austenitic after it reaches room temperature. As a matter of fact, a rather high carbon content and the most drastic quenching are both required to allow retention of austenite, but it is theoretically possible in any steel.

Less rapid cooling than that necessary to retain austenite but more rapid than that which produces the normal change to stable ferrite and pearlite, is required for hardening. By such a rate of cooling, products are obtained which are metastable from the phase-rule point of view and have no place in the regular equilibrium diagram. These products are essential for heat-treatment, and no hardening is possible unless a rate of cooling is used which will produce the metastable products.

When the rate of cooling is increased to this point there appear, instead of the normal Ar_1, two new critical points, one at a temperature slightly below that at which Ar_1 appeared at the next slowest rate and a second point at a very much lower temperature. When two critical points thus appear, we have the phenomenon known as a "split transformation." Part of the austenite changes at the upper point and part is preserved and changes at the lower point. The gap between the upper point, termed Ar' and the lower, termed Ar'', may be several hundred degrees Centigrade.

At Ar' the product is primary troostite; at Ar'' it is martensite. Both probably are unstable, from the phase rule point of view.

As the rate of cooling is further increased, Ar' becomes weaker, less primary troostite is formed, and Ar'' becomes stronger and more martensite is found. The temperatures at which Ar' and Ar'' start to occur are progressively lowered, that of Ar' generally falling more rapidly than that of Ar''. Simultaneously, the thermal effect at Ar' decreases in intensity while that at Ar'' is accentuated until finally, at some definite cooling rate, Ar' is entirely absent and only Ar'' occurs.

This is the necessary condition for complete hardening, since martensite is the product required in a hardened steel.

Still further increase in rate of cooling may partially suppress the occurrence of Ar'' and preserve some austenite unchanged, giving a mixture of austenite and martensite. Still further increase in rate brings us to the limiting case of complete retention of austenite.

The failure of austenite to go over to the stable phases, its transformation to unstable materials, or its failure to transform at all, mean that

there is a tendency for the decomposition of austenite to be sluggish. Austenite is the more sluggish the higher the amount of dissolved carbon. If the carbon has not diffused uniformly so that in some parts of a "cored" austenite crystal the carbon content is lower than the average, its tendency to change is that of the portion lowest in carbon. The change, once started, progresses throughout the entire crystal.

The cooling rate which will prevent the sluggish austenite from wholly or partly changing over depends on the carbon content and on the uniformity of distribution of the carbon, and the latter depends on the facilities for diffusion (maximum temperature and time), which the austenite had on heating. Hence for each carbon content and for each maximum temperature (including the time factor with the larger one of temperature) to which the austenite has been heated, there is some definite range of rates of cooling in which range Ar_1 may be lowered, but austenite will still change to ferrite and pearlite. There is a definite range of rates of cooling at which that change will cease and the split transformation will begin; a definite range of rates through which the upper critical, or primary troostite point, Ar' decreases in intensity and the lower, or martensite, point Ar'' increases; and finally, there is a definite rate of cooling at which martensite alone is formed.

In the above discussion, we seem to be on firm ground. Controversial matters such as the existence of β iron, the constitution of primary troostite and of martensite, etc., have not been touched on. Discussion of the current theories regarding these points would tend to obscure the problem rather than to clarify it. There is some discussion [7] as to whether Ar' and Ar'' are separate inversions, distinct from Ar_1 or whether they are parts of Ar_1 held up to occur at lower temperatures. They are here considered as distinct.

Having once obtained martensite by a suitable rate of cooling, it may be tempered by raising the temperature (time being also a factor), the unstable martensite breaking down; first, to secondary troostite; on further tempering, to sorbite. There should be noted here the distinction between primary troostite, formed directly from austenite, and secondary troostite, formed by the breakdown of martensite. The two are distinct products, from the metallographic standpoint.

How Alloying Elements Affect Heat-Treatment. Alloying elements influence heat-treatment by making it possible to produce the split transformation at a lower rate of cooling. They tend to make austenite more sluggish.

If we maintain the same composition of the steel, the same maximum temperature to which austenite is heated, and change the rate of cooling, a set of cooling curves at different rates can be obtained [7] showing at

which cooling rate the split transformation appears, and at which rate Ar″ (martensite) only appears.

Special apparatus [278] is required to obtain such curves on low carbon steels and on some alloy steels which only show the split transformation at very rapid cooling rates.

Or, we may maintain the composition, select one definite cooling rate, and vary the maximum temperature [8, p. 193] to which the austenite is heated. A steel with a marked propensity toward hardening will show, at a cooling rate readily handled experimentally, the appearance of the split transformation and the gradual disappearance of Ar′. The basis of comparison is then the temperature of the austenite required to produce the split transformation, and that required to eliminate Ar′.

With a definite cooling rate and definite maximum temperature we may change the composition, and find out, for a definite carbon content, what alloy content is required to produce Ar′ and Ar″. Or, with a definite alloy content, we may similarly study the effect of carbon.

The familiar "Guillet diagrams" [8, p. 173; 6, p. 336] show the carbon and alloy compositions with which alloy steels, on cooling in air from the same maximum temperature, are respectively pearlitic (*i.e.*, are not air-hardening), martensitic (*i.e.*, are air-hardening), or austenitic (*i.e.*, all transformations are suppressed). These diagrams do not tell much about the ease with which the steels that are pearlitic on air cooling can be hardened by quenching. For a comparison of alloying elements as to the degree to which they make austenite sluggish, sets of curves to show the critical rate or the temperature which the austenite requires to show "splitting" offer a better laboratory method of showing the effect of the [4, p. 175] alloying element on the tendency of the austenite to decompose. This restraining effect is variously termed "obstructing power" [4, p. 175], "retarding power," "brake action," or "stabilizing effect." Harder [9] says the alloying elements may be regarded as catalysts which accelerate or retard the rate of solution or precipitation of carbides. Another explanation of "stabilization" couched in terms of the modern conception of crystal structure, is that stability of the austenite is brought about by entrance into its space lattice of atoms of different size or of different field of force. This is assumed to make difficult the change [265] of α to γ iron. With more knowledge of the disposition of alloy atoms in the austenite space lattice, a quantitative explanation of the strong retarding power of some alloys and of the almost negligible effect of others may be forthcoming.

The alloying elements vary as to the temperatures at which Ar″ occurs (martensite is formed). If it occurs at a relatively high temperature, say 550° C. (1025° F.), it may happen that in air-cooling, the steel may harden completely to the martensitic state, but the martensite is

formed at so high a temperature that it has opportunity for self tempering during air-cooling, *i.e.*, the rate of cooling in air may be insufficient to preserve the martensite and prevent its further decomposition to troostite or sorbite.

If Ar″ occurs at a lower temperature, say 350° C. (660° F.), at which martensite is relatively stable and tempers but slowly, air-cooling may be rapid enough to preserve the martensite. The propensity toward hardening on quenching may be greater in the former case than in the latter, but the latter steel would be fully air-hardening while the former would not.

Hence the influence of the alloying element on the temperature at which inversions start as well as on the rapidity with which the inversion takes place when once started, must be considered.

Modification of steel by the introduction of an alloying element or elements, so that only Ar″ is produced at a relatively slow rate of cooling, is necessary in order to avoid the "mass effect." [10, p. 70] When the rate of cooling is on the dividing line between one which will give only the normal transformation to ferrite and pearlite and that which will give some martensite, it may readily occur that the outside of a large piece of steel may be cooled rapidly enough in quenching to give a hard martensitic outside, while the inside cools enough less slowly so that little or no martensite is formed. The hardness and strength of the inside of such a piece may be much lower than that of a smaller piece.

Alloying elements may make the austenite so sluggish that the slower rate of cooling at the center is as effective as the more rapid one at the outside. For example, in heat-treating by oil-quenching and tempering, a 0.45 per cent. C steel may show 35 per cent. lower elastic limit when heat-treated in 3-inch diameter than when treated in ¾-inch diameter. A steel containing 0.30 per cent. C, 1.0 per cent. Cr may show 25 per cent. lower elastic limit in the larger size. This latter steel with 0.80 per cent. Mo added would show an elastic limit lower by not over 10 per cent. in the larger sizes, and a steel containing 0.30 per cent. C, 3.25 per cent. Ni, and 0.85 per cent. Cr would scarcely show 5 per cent. difference in elastic limit. As will be shown later by cooling curves, the chromium-molybdenum and the nickel-chromium steels possess a very sluggish brand of austenite.

Aitchison [10, p. 203] says "The important point about the selection of a steel which shall avoid the evil effect of mass is that the steel chosen, though it may not harden completely in air, should yet harden to some appreciable extent after this treatment."

Guillet and Portevin [8] also classify alloy steels according to the effect of the alloying elements on lowering and splitting of the critical points on cooling.

Since all hardening depends on the control of the breakdown of austenite, the slowing up of this breakdown by an alloying element makes possible far better control of heat-treatment than is possible with carbon steel. In many engineering applications, where the relatively mediocre properties required could be provided by carbon steel, it is found advisable to use an alloy composition because of the less exact control of heat-treatment demanded by the latter.

Effect of Alloying Elements on Tempering. The latitude in heat-treatment conferred by alloy elements applies not only to the quenching or hardening operation, but to the tempering or softening operation as well. Alloy steels as a class resist tempering more than do the carbon steels. Not only do the former tend to harden more completely, but, if equally hardened specimens of the two classes are compared we find that the same draw temperature gives a softer and weaker product with the carbon steel than with the alloy steel.

The resistance to tempering is usually great in these alloy steels, which show the greatest propensity toward hardening. While there may be no direct connection between the two phenomena, it nevertheless frequently happens that the steels containing enough of suitable alloying elements to make the austenite sluggish in breaking down into martensite are also sluggish in decomposing to secondary troostite and sorbite, and the sorbite especially is reluctant to soften further.

According to Scott [(11)] silicon and chromium tend to make martensite delay its transformation to secondary troostite until higher temperatures are reached, as shown by heating of the hardened steels, while the other alloying elements do not change the transformation temperature. The troostite-sorbite change and the stages in the coarsening of sorbite cannot be followed by heating curves.

This sluggishness towards tempering allows a good many alloy steels to be drawn for long times at relatively high temperatures without unduly softening the steel. But it is generally accepted that the release of internal stresses, [(10, p. 114)] set up in quenching, increases with increase in draw temperature as well as with time at a given temperature. Alloy steels may thus be made much freer from internal stress than carbon steels of equivalent physical properties.

Not all the elements used for alloying with steel exert all the effects above noted, and the percentage of the various elements required to produce a certain result may vary widely. Nevertheless, the benefits conferred by most alloying elements are quite similar in nature, though varying in degree. It gives a very nearly correct view of the alloy steel situation to consider that, by suitable adjustment of the content of carbon, manganese, chromium, nickel, vanadium, molybdenum, etc., we can produce

by proper heat-treatment an almost unbroken gradation of mechanical properties and engineering usefulness, ranging from an annealed low carbon steel on one end to an air-hardened nickel-chromium-molybdenum-vanadium steel on the other. Even high-speed tool steel, though differentiated from the structural and automotive steels by the special carbides present, fits in on the end of the series.

Chapter 2.

Effect of Alloying Elements as Individuals.

By proper substitution of alloy elements it is almost invariably possible to replace an alloy steel, of given properties, with another steel which is identical from the engineering [10, p. 165] point of view but of greatly different chemical composition. The alloying elements vary in their effect on grain growth of austenite, on the tendency to crack during quenching, on thermal and electrical conductivity, on thermal expansion, on ease of case-hardening, etc.

We can therefore consider the alloying elements from the point of view of their ability to impart the effects mentioned above as characteristic of alloying elements as a class, and may also examine them for any unique individual effect.

The trump cards in the pack of alloy elements are nickel, chromium, vanadium, and molybdenum. Carbon occupies a unique position and might be termed the joker.

Manganese and silicon are both useful alloying elements and valuable scavengers. The other elements often have some effect as alloys, some are scavengers of a sort and may be of more or less value; others, like phosphorus and sulfur are usually deleterious and not intentionally introduced into steel.

Carbon. The characteristic effect of carbon in steel is so well known that it need not be reviewed here. Carbon, being essential to steel by definition, can hardly be classed as an alloying element, but obviously it is the most important element even in an alloy steel. Alloying elements accentuate differences in carbon content and a range in carbon permissible in carbon steel without variation in heat-treatment, may be far too great in an alloy steel.

Manganese. The primary rôle of manganese, that of taking care of sulfur by forming manganese sulfide and preventing the formation of iron sulfide which causes hot-shortness, makes it an essential constituent of steel. In order to insure, by mass action, the absence of iron sulfide, it is necessary to introduce more manganese than the chemical equivalent of the sulfur. For this purpose some three times the theoretical amount of manganese is generally considered necessary. [12, 279] For a sulfur content of 0.05 per cent. about 0.08 per cent. Mn is theoretically

required, so that 0.25 per cent. Mn should be ample to insure control of the sulfur.

But manganese has another rôle, that of deoxidizer, and is necessary for control of oxygen. Even low carbon "effervescing steel" (13) contains 0.35 per cent. or 0.40 per cent. manganese.

Under normal steel-making conditions, 0.35 per cent. Mn is about the minimum required to provide the scavenging necessitated by the presence of sulfur and oxygen. Much steel carries a higher manganese content in order to give a factor of safety. The excess above the requirement for scavenging may properly be considered as an alloying element.

As an alloying element, manganese slightly lowers the Ac range.(14) According to Hoyt (15, p. 239) it retards grain growth and makes steel less sensitive to the effect of high temperatures in rolling, but according to Bullens (5, p. 345) manganese steel increases in grain size very rapidly at high temperatures.

The obstructive power of manganese on the decomposition of austenite is very marked. Lowering and splitting of Ar_1 occurs readily in steels of say 0.60 per cent. to 1.00 per cent. C and 1 to 2 per cent. Mn. With 2 per cent. Mn, 1 per cent. C, even Ar'' can be suppressed by drastic quenching. On increasing the manganese to about 12 per cent. and holding the carbon at about 1 per cent., the steel is austenitic even on air-cooling, *i.e.*, such a composition gives the Hadfield austenitic manganese steel of commerce, with its great resistance to wear and accompanying impossibility of commercial machining.

For many years it was believed that steels of much over 1 per cent. manganese were useless for heat-treatment because of brittleness, splitting and cracking on quenching, and because of brittleness even after tempering to sorbite. With great care to produce such steels free from non-metallic inclusions, to avoid grain growth before quenching, and to quench uniformly, these steels are found to be of distinct value so that use of manganese as a true alloying element is increasing.(5, p. 95) (16) (17) (18) (28)

In steel castings, for example, we have the data in Table 1, on page 30. from Hall, Nissen and Taylor.(19)

Comparing *a* and *b* it is seen that an added 1 per cent. manganese makes the steel semi-air-hardening, so that air-cooling of *b* is as effective as water-quenching of *a*. Comparing *e* and *d* with *a*, it is seen that by decreasing the carbon and increasing the manganese a steel of superior elastic limit can be produced.

Aitchison (10, p. 145) cites figures on 0.32 per cent. carbon steels with 0.73 per cent. and 2.50 per cent. manganese respectively, showing that the mass effect on hardening is distinctly less and the propensity toward hardening much greater with the steel of higher manganese content. This effect is characteristic of elements which tend to make austenite sluggish,

TABLE 1

	Composition			Mechanical Properties			
No.	C	Si	Mn	T. S.[a]	E. L.	Elongation	R. A.
a	.37	.40	.80	85,000	50,000	21	29
b	.37	.25	1.75	90,000	50,000	16	32
c	.25	.40	1.35	109,000	70,000	21	29
d	.26	.55	1.15	83,000	51,000	30	58

No.	Heat Treatment
a	900° C. (1650° F.), water; 680° C. (1255° F.) draw
b	900° C. (1650° F.), air; 700° C. (1290° F.) draw
c	900° C. (1650° F.), water; 700° C. (1290° F.) draw
d	900° C. (1650° F.), water; 630° C. (1165° F.) draw

[a] Tensile strength (T. S.), proportional limit (P. L.), elastic limit (E. L.) and yield point (Y. P.) throughout the book, are in pounds per square inch. Elongation (El.) is in per cent. in two inches and reduction of area (R. A.) in per cent.

Even in steel as rolled the strengthening effect of manganese is evident as Webster (20) shows. With 0.10 per cent. carbon the tensile strength rises from 64,000 to 66,000 as manganese rises from 0.35 per cent. to 0.75 per cent. and with 0.75 per cent. carbon from 126,000 to 148,000 as manganese rises from 0.35 per cent. to 1.15 per cent.

Neville and Cain (21) have examined the iron-carbon-manganese alloys up to 1.6 per cent. carbon and 1.6 per cent. manganese, and their work shows not only that manganese exerts a strengthening effect of its own, but that in presence of manganese the strengthening influence of carbon is increased.

A great many alloy steels ordinarily carry up to 0.75 per cent. manganese and while a 0.50 per cent Cr, 0.75 per cent. Mn steel would ordinarily be called chromium steel, the properties of the steel would be in no small measure due to the manganese. Strauss (16) emphasizes the value of manganese as an alloying element, and states that, while the steel in the range 1 to 2 per cent. manganese is "tender" and requires careful treatment, if properly heat-treated it is not brittle.

Manganese enters both into ferrite and into cementite, so that instead of α iron and Fe_3C the phases are an α solid solution of iron and manganese and a complex iron-manganese carbide.

Silicon. In the amounts usually found in steel, say under 0.20 per cent., silicon is not classed as an alloying element. Its function is as deoxidizer and densener, *i.e.*, to "swamp" the dissolved gases and hinder their evolution to form blowholes as the metal freezes.

As Aitchison (10, p. 159) points out, high silicon content in a Bessemer steel is an indication of too hot a blow, so that specifications for such steel were originally drawn to demand a low silicon content, not because the silicon in itself was harmful but because it indicated an undesirable stage of manufacture.

Basic steel is kept low in silicon because additions of silicon will become somewhat oxidized during its introduction and the SiO_2 formed will attack the basic refractories. Acid steel carries more silicon than that made by the basic process.

Silicon goes into solid solution in ferrite, though it may be in solution as an iron silicide rather than as silicon. It is also possible that an iron silicide isomorphous with Fe_3C (22) may form a solid solution with the cementite. It is quite unlikely that silicon is ever present as carbide.

Silicon has a small strengthening effect.(46) Webster (20) shows that, for a given carbon and manganese content, rolled steel is stronger when it contains more silicon. Hoyt (15, p. 242-253) points out that strength may be increased without lowering ductility by lowering the carbon and raising the silicon. Meacham (23) (6, p. 352) shows that silicon raises the Ac_1 and Ar_1 points by about 30° C. (50° F.) for each per cent. of silicon, while the Ac_2 point shows little or no change. In raising Ar_1 instead of lowering it, silicon acts differently from the general class of alloying elements. Nevertheless, it appears to increase to some degree the intensity of hardening on quenching. This may be due to the effect on the eutectoid composition.(24) Silicon tends to increase the grain size, especially when present in amount over 2.5 per cent. In still higher amount, around 5 per cent. it tends to cause the precipitation of graphite in the steel, and thus causes marked brittleness, which is greater at low temperature. (25)

Low-carbon silicon steel sheet with, say 0.10 per cent. carbon and 3 to 4 per cent. silicon finds large use in transformer manufacture,(26) as it has low hysteresis loss and high permeability. Silicon steel cores are said to have saved, in the last 20 years, electrical energy that would otherwise have been lost in the transformers in amount so great that its value would build the Panama Canal.(27)

Silicon increases the electrical resistance greatly. It hinders case-hardening. It lowers the co-efficient of expansion.

With large amounts of silicon the iron-silicon alloys become too hard for machining, are very brittle, and cannot be rolled or forged. They must be shaped by casting. The high silicon alloys of this class are very resistant to corrosion.

This non-corrosive property is present in some degree in the lower silicon steels. Increase in silicon makes ferrite more resistant to etching, and silicon up to about 4 per cent. is used in conjunction with chromium in some types of stainless steel.(29)

In comparison with other alloy steels, the uses of silicon for transformer and acid-resisting steels may be considered special non-competitive uses. Competitive use is practically limited to spring and gear steels of 0.40 per cent. to 0.60 per cent. carbon, about 0.75 per cent. manganese and around 1.25 per cent. to 2.0 per cent. silicon, which are called silico-

manganese steels. Very good static properties may be developed [30, p. 52] in such steel by heat-treatment, *e.g.*, 250,000 tensile strength, 231,000 "elastic limit," 9 per cent. elongation, 40 per cent. reduction of area. But duplicate specimens showing this strength may only give 2 per cent. elongation and 4 per cent. reduction.[15, p. 358] [5, p. 352] These steels are very sensitive to slight changes in heat-treatment, are likely to crack in quenching, and may give very low results in single-blow notched-bar impact tests. They are cheap, and useful when made with the greatest care, so as to produce a uniform and reliable product, but the difficulties in the way of producing a truly reliable product are rather great. At present attention is being paid to similar steels containing less carbon but with added nickel. Data on steels of this type will be found in Chapter 11.

Chromium. Chromium shares with nickel the commanding position among true alloying elements. One of these two metals is used in most present-day commercial alloy steels. Chromium is most often used in conjunction with another alloying element such as nickel, vanadium or molybdenum. However, by suitable heat-treatment a simple chromium steel can be given a range of properties far exceeding the range of plain carbon steels, and well into the range of the more complex alloy steels.

In a recent patent, Zimmerschied [291] states that a plain chromium steel, properly made, and refined in the electric furnace to below 0.01 per cent. P and 0.025 per cent. S, and freed from oxides and other "dirt," will give the same properties without vanadium or other "vanadium-like elements" as when such additions are made.

Unlike manganese and silicon, chromium has little or no deoxidizing or scavenging power, and is used solely as a true alloying element. In small amounts chromium acts primarily as a carbide-forming element and tends to produce a complex and a stronger cementite. It lowers the eutectoid percentage of carbon. When the percentage of chromium is high, as in stainless steel, the alloy enters the ferrite as well as the cementite.[75, 323]

Increase in chromium content raises Ac_1, very materially, while Ac_2 is unaffected. In 0.35 per cent. carbon steel, with chromium content up to about 2 per cent., Ar_1 is raised. With 7 per cent. chromium in 0.35 per cent. carbon steel, or 3 per cent. in 0.80 per cent. carbon steel, the split transformation readily appears. The appearance of the split transformation is dependent on both the carbon and chromium content, as well as the maximum temperature and rate of cooling. [33, 34]

With the usual chromium content of automotive plain chromium steel, say up to 1 per cent., splitting is not readily noted at the relatively slow cooling rates used in taking critical point curves. With increase in the maximum temperature to which the austenite is heated, Ar_1 may be pro-

gressively lowered, the more readily the higher the carbon.(6, p. 349) (15, p. 367) (31) (35)

With a relatively low maximum temperature, Ar_1 will be raised by increase in chromium, but Ar_1 for such conditions, may then by lowered by raising the maximum temperature. Many of the data on these points have been obtained on chromium-vanadium steels instead of plain chromium, which makes it difficult to draw definite conclusions on the effect of chromium alone. Aitchison (10, p. 70) gives cooling curves for steel (carbon content not stated) of 2 to 3 per cent. chromium taken from different maximum temperatures. In these the start of the Ar_1 range is progressively lowered as the temperature rises, but during recalescence the steel regains the same temperature in all cases. The tendency toward undercooling is very plain although the inversion is not split nor its maximum lowered in temperature. With carbon and chromium both high, carbides of exceptional hardness are formed and the stability of these may vary with temperature so that the carbide may break down, freeing chromium which may then be taken into solution in austenite, producing sluggishness, developing the split transformation, increasing the propensity for hardening, and reducing the mass effect in hardening.

This tendency is present, though not strongly marked, in low carbon and chromium steels. While the carbon and chromium are not in themselves sufficient to produce much depth-hardening and allied phenomena, it requires a smaller addition of a third element to bring these phenomena into play than would be calculated from the behavior of the third element alone. Chromium is therefore generally augmented by some intensifying element, the net result being obtained more cheaply or readily than with either element alone.

The equilibria with high chromium and carbon are complex and, while much work (10, p. 370) (31) has been done on the subject the relations are not yet wholly clear. Even with 0.40 per cent. carbon and 3 per cent. chromium, the carbide is very slow to go into solution in austenite on heating, and equilibrium conditions are hard to obtain.

On account of the peculiar hardness and strength of carbides containing chromium, many chromium steels are made of hypereutecoid composition to obtain the benefit conferred by the free carbide. Chromium is an essential constituent of high speed tool steels. Ball bearings, with their phenomenal resistance to crushing and to wear, contain about 1 per cent. to 1.40 per cent. each of carbon and chromium. Higher chromium and lower carbon give a steel at one time used for armor-piercing projectiles and still used for cold-rolls. With only 0.5 per cent. chromium and a low carbon content, case-hardening steels are produced which not only are readily case-carburized, but in which the case is of exceptional hardness due to the formation of chromium-bearing cementite or double carbide. With

about 0.40 per cent. carbon and 0.50 per cent. chromium a steel suitable for heat-treatment is produced which, at equal ductility with a corresponding carbon steel, is 10 to 15 per cent. stronger.

With still more carbon, 0.80 per cent. to 1 per cent., still with 0.50 per cent. chromium, a class of tool steels useful for chisels, razors, etc., is developed; and, on account of the presence of some double carbide, the slightly hypereutectoid steels have considerable "wearing hardness" even in the annealed condition. This gives them a fairly tough matrix, and makes them of value for stamp and crusher shoes.

The 0.50 per cent. chromium steel with 1.3-1.5 per cent. carbon makes an excellent file. The standard automotive type of hypoeutectoid chromium steels give results as shown in Table 2.(5, p. 295) (10, p. 294) (15, p. 274) (295)

TABLE 2

	Composition			Mechanical Properties			
No.	C	Mn	Cr	T. S.	E. L.	Elongation	R. A.
a	.47	.60	.51	168,000	154,000	19	53
b	.70	.60	.50	169,000	145,000	12.5	34
c	.40	.55	1.00	160,000	137,000	15.5	57.5
d	.64	.28	1.04	186,000	127,500	10	22

No.	Heat Treatment
a	795° C. (1460° F.), water; 540° C. (1000° F.) draw
b	760° C. (1400° F.), oil; 540° C. (1000° F.) draw
c	790° C. (1450° F.), oil; 540° C. (1000° F.) draw
d	870° C. (1600° F.), oil; 600° C. (1110° F.) draw

Chromium in fairly large amounts has the property of making steel very resistant to corrosion. "Stainless" steel with about 0.30 per cent. carbon and 12 per cent. chromium has recently become of much importance on account of its great resistance to atmospheric corrosion and to many acids, especially organic acids.(36) (37) (274) (297) (298)

Steel of this composition is of eutectoid composition, due to the influence of chromium. It is air-hardening if cooled from 950°-1000° C. (1740-1830° F.) oil-hardening from 900° C. (1650° F.). Higher carbon allows the use of lower hardening temperatures. On account of the elevation of Ac_1 and the slowness with which the carbide goes into solution in austenite, forging and quenching for hardening have to be done at very much higher temperatures than in more common steels. Hardening must take place if the full stainless property is to be developed.

Stainless steel is also of promise as a structural material. Aitchison, (10, p. 210) points out that not only can it be made to give good strength, but that its strength can be reduced by tempering so as to give a soft steel, softer than is possible with most other alloy steels capable of being given similar maximum strength. The possible range of properties is shown by the following, for a 0.40 per cent. C, 12.2 per cent. Cr steel air-hardened from 900° C. (1650° F.)

TABLE 3

Draw-Temperature ° C.	° F.	Tensile Strength	Yield Point	Per Cent. Elong.	Per Cent. R. A.	Izod Foot Pounds
400	750	230,000	208,000	7.5	12	6
750	1380	113,000	94,000	28	52	30

Parmiter [298] gives a table of tensile properties of a 0.30 per cent. carbon, 13.0 per cent. chromium steel, quenched from 990° C. (1825° F.) and drawn at temperatures ranging from 290° C. (550° F.) to 815° C. (1500° F.). From this the following figures are taken.

TABLE 3a

Draw-Temperature ° C.	° F.	Tensile Strength	Yield Point	Per Cent. Elong.	Per Cent. R. A.	Brinell
510	950	259,000	203,500	8	19.5	480
565	1050	225,000	191,500	7.5	32	425
625	1150	175,000	145,000	10	32	375
675	1250	151,000	125,500	12	39	325
730	1350	140,500	114,000	13.5	43.5	305
760	1400	131,000	104,000	14.5	46	285
	Annealed	100,000	65,000	27	59	175

With lower carbon, the so-called stainless iron, of 0.10 per cent. or less carbon and about 11-15 per cent. chromium is produced. This is really a true steel because even such a carbon content is about one-third the eutectoid composition for that chromium content, and it is susceptible to heat-treatment. Oil-quenched from 950° C. (1740° F.) it gives:

TABLE 4

Draw Temperature ° C.	° F.	Tensile Strength	Yield Point	Per Cent. Elong.	Per Cent. R. A.	Izod Foot Pounds
500	930	177,000	....	20	57	20
600	1110	122,000	101,000	26	63	26
700	1290	87,000	97,000	28	66	115

Higher percentages of chromium, upwards of 20 per cent., give alloys of very promising properties [38] which need not be considered here.

The simple chromium steels thus extend over a wide range of chromium and carbon content. The outstanding effects of chromium in heat-treated steel are the production of increased strength without increased brittleness, production of a fine-grained steel, and a tendency toward air-hardening. The reduction of the eutectoid percentage of carbon by the entrance of chromium is very marked. Chromium-bearing cementite is harder and stronger than plain Fe_3C, and in the hypereutectoid steels still other carbides of chromium of very great hardness are found. It is obvious that chromium not only belongs in the general class of alloying elements, but also has many marked individual effects.

Vanadium. Vanadium is another element which readily forms a carbide, and very little vanadium is thought to be dissolved in ferrite,[39]

the bulk of it being in the cementite as a complex carbide or in solid solution. It differs markedly from chromium in that it is a deoxidizing and scavenging element and, although too expensive to be primarily used for that purpose, its addition doubtless assists in the thorough deoxidation of steel. It is also claimed to remove nitrogen. Its chief function is as an alloying element and, as such, it is unique in the very small amounts required. Hypoeutectoid alloy steels, in which vanadium is used, carry only 0.15 per cent. to 0.20 per cent. vanadium and no advantage seems to be gained by increasing the amount.

In modern high-speed tool steel, vanadium is considered almost as essential as the tungsten and chromium and in such steel about 0.75 per cent. to 2 per cent. is regularly used, [(280)] especially as it is claimed that 13 per cent. tungsten plus 1 per cent. vanadium is equivalent to 18 per cent. tungsten without vanadium.[(15, p. 452)] Attention will here be confined to the steels with small amounts of vanadium.

In these small amounts, vanadium appears to have, in itself, but slight effect on the critical ranges.[(32) (33) (39)] It probably acts as chromium does when the percentage of chromium is low, *i.e.,* to raise both Ac_1 and Ar_1 and it does not cause marked lowering of Ar_1 on raising the maximum temperature. In conjunction with chromium, it seems to accentuate the effect of the latter element. While it does not readily cause the split transformation, it probably exerts a very slight tendency in that direction and gives somewhat greater propensity toward hardening. This action is so slight that the behavior of 0.20 per cent. vanadium can hardly be said to class vanadium among potent alloying elements on this score, and its alloying effect is more that of an individual than as a member of the class of elements which stabilize austenite.

Its specific action is notable in that it greatly reduces the tendency toward grain growth of austenite on heating. Temperatures that would ruin an analogous plain carbon or plain chromium steel are not only harmless with vanadium present, but are required to produce the best results.

It may be that the beneficial effect of vanadium is largely that of preventing grain growth of austenite, so that the properties of plain vanadium steel may largely be those of plain carbon steel, could the carbon steel be safely heated to the same temperature and held as long before quenching.

Vanadium steels are characterized by exceptional fineness of grain. Either the trace of vanadium in solution in ferrite obstructs diffusion or vanadium-bearing cementite can diffuse less readily, so that the sorbite of vanadium steel tends to be finer, with less agglomeration of cementite and separation of ferrite than without the vanadium.

This fine grain is probably the reason for the outstanding mechanical properties of heat-treated steels containing vanadium and the high elastic

limit in comparison to the tensile strength and ductility. The elastic ratio of vanadium steel is certainly as high as, and often higher than that of any other common alloy steel. Moreover, vanadium exerts this influence on the elastic limit in the presence of other elements. For cases where a high static elastic limit is needed, vanadium thus serves a useful purpose. It is also believed to increase ductility slightly.

Vanadium is also reputed (40-42) (43, p. 532) to have a specific influence on the ability of a steel to resist repeated stress, and scarcely a text-book discussion of vanadium (5, p. 337) (43, p. 532) will be found without a reference to the "fatigue-resisting power conferred by vanadium." Vanadium steel does have a good record on this score, both in service and in laboratory tests, (264) but, as will be brought out in Chapter 8, the importance of vanadium for this purpose has certainly been exaggerated.

Some of the highest authorities flatly challenge the statement that vanadium is of any real value whatever. Aitchison, (10, p. 192) speaking of chromium-vanadium steel, says that "as far as mechanical tests are concerned, just as good results are obtained if the vanadium is omitted entirely and a plain chromium steel used." He criticizes the commercial chromium or chromium-vanadium steels for being prone to suffer from the effects of mass during hardening, due to their relatively inferior air-hardening properties. Bullens (5, p. 335) is not convinced of the value of vanadium.

Nevertheless, one of the important advantages of vanadium for one particular use is that it does not confer marked air-hardening properties. In complicated shapes, such as locomotive frames, castings, and large forgings of irregular shape which would be almost certain to crack in the quenching process during heat-treatment, but in which a high static elastic limit is required, normalized or annealed plain vanadium steel finds considerable application. If the steel were wholly or partly air-hardening, normalizing would produce material of lower elastic limit. Concrete examples will be presented in Chapter 9. The usual 0.20 per cent. vanadium is said to raise the tensile strength of annealed cast steel (0.28 per cent. C, 0.25 per cent. Si, 0.57 per cent. Mn) from 65,000 to 80,000 pounds per square inch and the elastic limit from 38,000 to 45,000 pounds. The properties of vanadium steel of various carbon content at different heat-treatments are given by McWilliams and Barnes and quoted by Hoyt, (15, p. 407) and those of vanadium steel with 0.35 per cent. and 0.50 per cent. carbon are given by Griffiths.(33) The latter steels also contain around 0.90 per cent. manganese, the alloying effect of which cannot be neglected.

Nickel. Nickel has no deoxidizing or scavenging action in steel; it is purely an alloying element. It goes into solution in ferrite and probably does not enter the cementite, although the existence of nickel carbide in cupro-nickel is well established and there is a possibility that nickel may

also modify cementite to some extent. Nickel lowers the eutectoid ratio. It also lowers the Ac range materially, so that hardening takes place from much lower temperatures than in carbon steels. Its effect on the critical ranges [7] on cooling is also very marked. Lowering of Ar_1 occurs, and at about 5 per cent. nickel, the split transformation appears. Ar'', the martensite point, is progressively lowered until at about 25 per cent. nickel it lies below room temperature and the steels are austenitic. High nickel steels have considerable resistance to corrosion and to oxidation at high temperatures. Nickel greatly increases the electrical resistance and lowers the coefficient of expansion of iron. With 36 per cent. nickel, as in "Invar," [44] the coefficient of expansion is practically zero at ordinary temperatures.

The increased propensity toward hardening, due to alloying elements as a class, is evident with nickel, but it requires over 5 per cent. nickel to make steel appreciably air-hardening. The common 3 per cent. to 3½ per cent. nickel steels show considerable mass effect in hardening, though they are superior in this respect to carbon steel. Although heat-treatment is necessary to bring out the maximum mechanical properties, nickel steel as rolled, or in the annealed or normalized states is appreciably strengthened and toughened over carbon steel. The strengthening is not so dependent on the carbon content as is the case with most other alloying elements. Hence the nickel steels are much used for case-hardening, since a tougher core can thus be produced than with carbon steel.

Nickel steel is gradually coming into use for structural work such as bridges [46] in which the weight of the steel itself forms a great part of the working load, but which are made of such large members that heat-treatment is impractical.

For most uses, however, the nickel steels are heat-treated. Commercial nickel steels for heat-treatment generally contain 3 per cent. to 3½ per cent. nickel with carbon up to about 0.45 per cent., the 5 per cent. semi-air-hardening grade also finding some use for special purposes. The low-carbon case-hardening steels run from 2 per cent. up to 5 per cent. or even 7 per cent. nickel.

Nickel decreases grain growth of austenite. It thus serves a double purpose in a case-hardening steel; it hinders deterioration from grain growth and gives inherent strength and toughness. The reduction of the eutectoid percentage of carbon decreases the amount of carbon that must be taken up before free cementite is present.

Nickel is rather expensive and it requires a considerable amount in an alloy steel to secure the strength usually required. Hence, instead of using a steel with a wide range of nickel content, to secure various gradations in properties, it is customary to "boost" the effect of nickel (exerted mainly on the ferrite) by that of chromium, which is exerted chiefly on the cementite. In this way a smaller amount of nickel, aided by a little

chromium, will give the equivalent of 3½ per cent. nickel. Addition of vanadium, of molybdenum, or an increase in manganese content, may serve a similar purpose. McAdam [47] believes that nickel steel has superior resistance to repeated stress. Stoughton [48, p. 429] makes a similar statement. Bullens, [5, p. 307] however, mentions without approving the statement that nickel "poisons" the steel dynamically.

Tungsten. Tungsten is another alloying element which exerts a strong effect. It is essentially a carbide-former, and in that behavior and in the complexity of the carbides that may be formed is analogous to chromium. To these carbides is due the hardness of high-speed tool steel.

Commercial use of tungsten is reserved for the high-speed tool steels and the magnet steels. The former contain 12 to 13 per cent. tungsten, together with chromium and vanadium, and the latter 3 per cent. to 6 per cent. tungsten. For cutting tools in which properties beyond the ordinary carbon tool steel are required, 3½ per cent. to 5 per cent. tungsten is often used, and in a few cases gun liners have been made of tungsten steel, because of its strength at high temperatures. It also enters into some gas engine valves.

An outstanding effect of tungsten is its effect on the critical points. [49-52] In hypoeutectoid steels with 2 per cent. to 3 per cent. tungsten, the split transformation is readily found on cooling curves, though it is necessary to carry the austenite to rather high temperatures. Increase of carbon and of tungsten increases the splitting and lowering. With about 1 per cent. carbon and 6 per cent. tungsten the steel becomes air-hardening. This composition plus a little chromium and a high manganese content is the old Mushet steel, the forerunner of modern high-speed tool steels.

The exact mechanism of the action by which tungsten makes austenite sluggish is still in dispute.

Tungsten lowers the eutectoid percentage of carbon.

Few data are available on the mechanical properties of hypoeutectoid heat-treated plain tungsten steels, by which tungsten might be compared with other elements. Bullens [5, p. 353] gives data for a steel containing 0.45 per cent. C, 0.30 per cent. Si, 0.22 per cent. Mn, 0.60 per cent. W. This was heat-treated by oil-quenching from 850° C. (1560° F.) and drawing at 500° C. (930° F.). Specimens showed 185,000 pounds tensile strength, 128,000 pounds elastic limit, and 7 per cent. elongation.

Molybdenum. Molybdenum is another carbide-forming element. Its position in the periodic table shows its similarity to tungsten, and in steel it acts much like tungsten, but more powerfully. It is commonly estimated that for some purposes, especially in high speed tools, 1 per cent. molybdenum is equivalent to about 2 or 3 per cent. tungsten. This statement is only roughly true.

The effect of molybdenum on the critical ranges (53-55) is more marked than that of tungsten, and small amounts will make steel air-hardening. The propensity toward hardening is shown by the presence of the split transformation, on relatively slow cooling, in steel with 0.40 per cent. carbon and 0.65 per cent. or less molybdenum. A little molybdenum, say 0.25 per cent., greatly augments the hardening propensity of a steel containing nickel, manganese, or chromium, in amount far too small to approach the air-hardening condition without the molybdenum. Of all the alloying elements now used commercially, molybdenum is the most potent in increasing the tendency toward hardening.

The presence of molybdenum increases the strength, even in the as-rolled condition; but, like most alloy steels, molybdenum steel requires heat-treatment to develop its best properties. Molybdenum closely approaches vanadium in its ability to inhibit grain growth of austenite, and in giving a high elastic ratio. When molybdenum is used alone, the steel is quite analogous to chromium steel. On account of its "boosting" effect, it is more often used together with chromium, and chromium molybdenum steels are now on a competitive basis with chromium-vanadium and nickel-chromium steels.

Heat-treated steels containing molybdenum, for the same strength, have a slightly higher ductility than many other similar alloy steels; or for equal ductilities, have a higher strength.

Perhaps the most important characteristic property of molybdenum steel is its exceptional resistance to tempering. In softening a molybdenum steel and any other comparable alloy steel after both are fully hardened by quenching, the molybdenum steel requires a very distinctly higher temperature or a longer time. This means that for a given set of mechanical properties, internal stresses may be released to a far greater extent with molybdenum steel. Inasmuch as the molybdenum steels have a slow quenching rate and require less drastic quenching for complete and deep hardening, the quenching operation may probably be so controlled that the initial internal stresses may be kept low, so that there is but little stress to remove by subsequent tempering.

Molybdenum steels in the sorbitic condition are extremely fine grained.

Claims have been made that molybdenum steels are superior in resistance to repeated stress. These, like the similar claims made for vanadium steel, appear to be exaggerations. This point will be fully discussed in Chapter 8.

In addition to the good mechanical properties and the ease of heat-treatment, molybdenum steels are said to be more easily machined than other alloy steels of equal strength.

Molybdenum has been substituted for tungsten in high-speed tool steel. While it may still find a place in such use, the consensus of opinion (56-58)

to date is that the cutting efficiency of such steels is not as uniformly good as in the standard type of steel without molybdenum. Molybdenum tends to vaporize, probably as oxide, from the surface of the tool at the very high temperatures necessary in hardening such tools.

Molybdenum has no deoxidizing or scavenging power. It is purely an alloying element.

Uranium. This element occupies a position in the periodic table near molybdenum and tungsten. Like them, it is a carbide-forming element and enters the cementite of steel. However, up to 2 per cent. it has no marked effect on the critical ranges nor does it markedly increase the propensity toward hardening. Its presence in conjunction with other alloying elements does appear to favor hardening to some extent, so that the tendency is present, but not strong.

The advocates of uranium (59) (60) state that no advantage is gained by going above 0.60 per cent. uranium and Poluskin (61) states that while it increases strength and toughness, it does nothing that cannot be as well accomplished by less costly elements.

Uranium is a very readily oxidizable element, and is very prone to leave its oxide products in the steel.(62) It is also likely to segregate badly.(63) (64) Great claims have been made for its use in high-speed tool steel and some such steel is regularly made with it, but the evidence is far from conclusive that it is of any benefit. Uranium may be classed as an alloying element which could profitably be studied intensively, were the potential supply larger.

Cobalt. This metal is chemically very similar to nickel, but does not appear to be of any particular advantage in ordinary steel. On the other hand, it is used in some of the best high-speed tool steels, while nickel is rigorously excluded from such steels. Alloys high in cobalt have recently been found (65) very useful for permanent magnets.

Copper. Many steels contain a few hundredths per cent of copper, but it is not disclosed because the conventional scheme of steel analysis ignores its presence. Copper up to about 0.25 per cent., or perhaps 0.50 per cent., tends to make low carbon steel more resistant to atmospheric corrosion, but less so to corrosion by water and simultaneously to strengthen the steel. It is stated,(281) however, that ship plates containing 1.67 per cent Cu, used on the Leviathan, showed great resistance to corrosion by salt water. Copper is recommended (282) for use together with chromium in corrosion-resistant steels. As an alloying element, it lowers Ar_1, much as nickel does, (15, p. 250) but less strongly. It can apparently replace some nickel (66) (67) in a nickel steel. Up to 0.6 per cent. copper is often used to replace an equal amount of nickel in steels made at the Naval Gun Factory. Not only does this cut down the amount of nickel required, but it can be added as Monel metal which contains nickel, copper, iron, and manga-

nese, thus affording a cheaper source of nickel. Jones (293), however, considers that copper in a nickel steel is without either good or bad effect.

The effect of copper in steel deserves further study.

Boron. Boron may also have possibilities as an alloying element, (43, p. 364) (67) (68) but owing to a low melting triple eutectic of iron, carbon and boron,(62) the steels are very tender and require low forging temperatures. Boron confers hardness and case-hardening with boron has been suggested.(69)

Cerium. Cerium is readily oxidizable and, like uranium, is difficult to introduce into steel without segregation and loss. Cerium can combine with sulfur and acts like manganese in preventing the formation of iron sulfide. Some sulfur may be eliminated by the use of cerium, but cerium steels retain some of the sulfur compound or some oxidation products of cerium as inclusions and are prone to excessive dirtiness.

Up to amounts which can be introduced without too much difficulty, the effect of cerium on the critical points,(267) the propensity for hardening and the mechanical properties seems to be very small. Tests on cerium steels are generally vitiated as far as showing the alloying action of cerium by the multitude of non-metallic inclusions present.

Cerium is probably present in steel, at least in part, as carbide. A steel containing 0.25 per cent. cerium gives a strong acetylene-like odor on exposure of a fresh fracture.

The behavior of cerium will be discussed more fully later.

Titanium. The alloying effect of titanium seems to be negligible, its only use being as a scavenger to remove oxygen and perhaps nitrogen. It seems to reduce segregation of carbon and of impurities. Some of the data cited by the advocates of titanium (70) (71) to show its value as a scavenger lie well within the range of results obtained without it and the proof of its usefulness is seldom clear-cut. A thorough study (72) of the deoxidation of rail steel by titanium and by silicon has been made by the Bureau of Standards. This shows that the action of titanium in restraining segregation is definitely shown only in the top of the ingot, that the average mechanical properties of the steel are not noticeably altered by titanium, and that the claim that the oxidation products of titanium do not remain in the steel is not in accord with the facts.

Stoughton (48, p. 206) believes that titanium causes occluded oxidized materials which would cause inclusions to be more readily separated from the melt, and Giolitti (73) mentions the use of titanium and vanadium as having specific action in developing fine grain on heat-treatment. Titanium probably serves a useful purpose as a scavenger, but it has no place in a list of true alloying elements.

Zirconium. Zirconium should be classed with its chemical sister titanium, as a possibly useful scavenger rather than an alloying element.

Much work [62] on zirconium in steels of the high silicon-nickel type failed to show any trace of true alloying behavior due to zirconium; or, at least, that it has any greater effect than so much silicon. Detailed data on some of these steels are given in Chapter 11.

Becket and Feild [12] [74] [76] [287] have produced far more definite evidence as to the scavenging value of zirconium in plain carbon steels than exists in the case of titanium. They show clearly that zirconium combines with sulfur, and may also eliminate some sulfur. This action is quite analogous to that of manganese and of cerium. It is claimed that steels treated with zirconium are unusually free from dispersed slag particles. Rather good evidence is also adduced to show that zirconium combines with nitrogen and it may decrease the total nitrogen content of the steel. In some way not yet understood, zirconium appears to reduce the brittleness, on impact test, due to high phosphorous content.

The mechanical properties of heat-treated carbon steel with small amounts of zirconium are changed but slightly and the average effect is that to be expected from increased cleanliness of the steel, *i.e.*, slight improvement in both strength and ductility, rather than an increased hardness and strength concomitant with lowered ductility, as would be expected from a true alloying element. Evans [286] states that while, for the production of a certain chromium-tungsten cutlery steel, he prefers to add silico-zirconium, the zirconium of which is practically eliminated before the steel freezes, he can at times get just as good results without zirconium, and only uses it because he finds that the properties aimed for are more readily obtained by the use of zirconium as a scavenger.

No data have yet been presented to show that zirconium has any alloying effect, either alone, or when present in combination with the common alloying elements.

Aluminum. Aluminum is another element with little or no outstanding evidence of true alloying effect, but which is widely used as a deoxidizer. Its presence in excess of the amount required for deoxidation is considered detrimental.[78] [79] It increases grain size in steel.

Although high authorities [43] [80] [81] state that deoxidation by aluminum should not be allowed, because of retention of alumina inclusions in the finished steel, practically no steel castings and very few ingots are made without the addition, in the ladle, of a small amount of aluminum to finish the "killing" of the metal. The use of aluminum as final deoxidizer is never advertised and is kept more or less under cover by steel makers.

Miscellaneous Elements. Other elements, like tantalum and columbium,[266] which might be expected to be useful have been but slightly investigated. Small amounts of arsenic [43, p. 533] appear to be without appreciable effect. Tin appears to be harmful in steel.

Elements Classed as Impurities

Phosphorus. In making alloy steel it is customary to hold phosphorus as low as possible to prevent "cold-shortness," *i.e.,* brittleness under impact. Phosphorus has a hardening and strengthening effect, and in very soft steel some carbon may be replaced by phosphorus. Phosphorus in steel shows a strong tendency toward segregation and the danger from this is the greater, the higher the phosphorus content and the higher the carbon. Consequently high-carbon or hard heat-treated steels are kept low in phosphorus.

Sulfur. Sulfur readily combines with iron to form iron sulfide and the presence of this compound makes iron and steel "red short." (279) To avoid red shortness manganese is added to steel in quantity sufficient to insure the conversion of practically all iron sulfide to manganese sulfide. The latter compound is insoluble in solid iron and is present as globules in the cast metal. At rolling or forging temperatures these globules soften and are elongated and drawn out to plates or threads. Their presence is shown by the reduced ductility exhibited by steel tested in tension along an axis normal to the direction of rolling. Because of their thread-like or lenticular form they exert but little effect in tests in which the tension loading is applied in the direction of rolling.

Manganese sulfide, like other non-metallic inclusions, is less dangerous in very soft steels than in hard ones.(283) In such material as rivet steel (82) a sulfur content as great as 0.10 per cent. may do no harm.

In hard steels, and in general, in heat-treated alloy steels, the sulfur content certainly ought not to be above 0.05 per cent. and the more nearly it can be completely eliminated, the better.

Tellurium. Tellurium reduces ductility of steel and shows no true alloying properties.(83)

Nitrogen. Nitrogen is an element which must be reckoned with in case-hardening with cyanide.(84-87) (284) It may also be taken up in small amounts, from the atmosphere, in melting steel and it may diffuse into solid steel, under certain conditions. Nitrogenized steel contains a needle-like constituent whose presence embrittles the steel.

Sawyer (88) studied practically pure carbon-free iron which had been nitrogenized and he found critical points indicating an iron-nitrogen equilibrium diagram analogous to the iron-carbon diagram. There was some evidence of a split transformation, more or less similar to that found in carbon and alloy steels. Other gaseous elements and compounds have been suspected of exerting specific, usually deleterious, effects on steel, but the examination of these effects is out of the field of this work.

Chapter 3.

Interchangeability of Alloying Elements.

The possibilities of alloy steels are greatest when more than one alloying element is used. The benefits of nickel in strengthening ferrite and of chromium in strengthening cementite can both be had when both elements are used. Vanadium exerts its greatest influence in inhibiting grain growth in austenite, in producing a fine grained sorbite, and raising the elastic ratio, in the presence of nickel or chromium, or of both. In these cases, as in those of increase in manganese, or of the addition of copper or of molybdenum to a nickel steel or to a chromium steel, the alloying effect of the chief element is augmented, as shown by increase in the capacity for hardening.

Either nickel or chromium is used as a base in most alloy steels. The possibilities of the cheap alloying elements, silicon, manganese, and copper, especially the latter, seem by no means to have been exhausted.

With the entrance of an alloying element into steel the carbon content generally requires reduction. When a second alloying element is used, the content of the first element is similarly reduced.

In adding two alloying elements, the effect obtained is usually greater than the sum of the effects obtained by adding the same quantities of the elements singly. That is, each element intensifies the effect of the other.

If we consider only the strengthening elements, carbon, silicon, manganese, nickel, chromium, vanadium, and molybdenum, and sort, according to tensile strength, the heat-treated steels that can be obtained by varying these elements, arranging them by increments of 25,000 pounds per square inch, we may then compare the heat-treatments required to give that strength, and may compare the elastic limit and the ductility with the tensile strength.

This has been done in Table 5. Many more examples could be given, such as steels similar to those of the table but varying in carbon content. The examples have been taken from various sources and the conditions under which the tests were made were varied. Some are average and some are single values. In some cases the proportional limit, in others the elastic limit, and in still others the yield point is given. The first and the last have definite meanings, but a writer who gives figures for

"elastic limit" without describing his test method, leaves the compiler in doubt as to just what the figures really mean. In this table, and in other cited data throughout, the term "elastic limit" has been retained when the article cited fails to show whether that term is used to refer to proportional limit, yield point, or some point between these two. All tests are on rather small sections, about 1 inch diameter and do not show appreciably the effect of mass. The data are for longitudinal specimens of forged or rolled material.

These tables may first be considered from the point of view of the engineer. If a tensile strength of only 100,000 pounds per square inch is needed, assuming that the elastic limit of the steel selected is adequate, it makes little difference for most engineering uses whether the elongation is 19 per cent. or 30 per cent., or the reduction of area 50 per cent. or 70 per cent. The lower values assure sufficient toughness for most purposes according to current engineering practice. However, Aitchison [89] considers that the heat-treatment which produces the maximum ductility gives the best steel, even though the tensile strength may be low.

In the section of Table 5 comparing steels of about 125,000 pounds tensile strength, the 0.45 per cent. carbon, water-quenched, carbon steel gives practically the same results as the alloy steels, the differences in proportional limit and ductility meaning little from the engineering point of view, as long as the comparison is based on small specimens. On large specimens the alloy steels would show much higher proportional limit.

The 150,000 pound group is at about the limit of machineability, though some machining operations can be performed on a production basis, with steels of somewhat higher strength. Nor is strength or hardness the only criterion of machineability—a property hard to define and still harder to evaluate quantitatively. In this group the 0.45 per cent. carbon water-quenched steel falls below the alloy steels in proportional limit and ductility. Raising the carbon brings up the proportional limit but drops the ductility still more. At about this strength the capabilities of the plain carbon steels begin to be exceeded and the alloy steels pull ahead. The presence of the alloying elements allows drawing at very much higher temperatures to get ductility without losing strength.

But it is very much a toss-up from the engineering point of view to make a choice among the different types of alloy steels. Any one of a half dozen compositions listed in the table might well serve the same purpose.

In the group showing 175,000 pounds tensile strength we are practically out of the useful range for carbon steels. At this strength they give both low proportional limit and low ductility. The alloy steels begin to show some differences among themselves, but the engineer still has a wide choice of materials with which he can attain a given result, especially

when small sections are being heat-treated. In large sections the mass effect, or the question of depth-hardening enters in, and the steels show individual variations as to mass effect, which is a vital factor in differentiating among the steels for industrial use. The mass effect will be discussed later, but even when it must be considered a fairly wide choice of compositions is often available.

At 200,000 pounds tensile strength the carbon steels are so low in ductility that they tend toward brittleness, but in all the alloy steels of this group the differences in proportional limit and ductility are practically within the range of variation in tests of duplicate specimens. One can use nickel, various combinations of nickel-chromium, nickel-vanadium, chromium-vanadium, nickel-molybdenum, etc., with practically equivalent engineering results.

The test results shown within the group at 225,000 pounds tensile strength are similar to those in the 200,000 pound group. However, it will be noted that steels containing molybdenum require a higher draw temperature than the other alloy steels. At 250,000 pounds strength, the spring-steel class, the carbon steels are out of it for severe service. To get this strength they must be used with scarcely any tempering; and are brittle. The strength of the carbon steel can be boosted and some ductility retained by raising the silicon or the manganese, or both; but to get maximum results there is generally used either high nickel or a combination of two or more of the most effective alloying elements.

At 250,000 pounds tensile strength and above, at least two strong alloying elements must be used to secure strength without brittleness.

A study of Table 5 indicates that a given set of mechanical properties may be attained through the use of any one of several compositions of steel. In his selection, for a specific application, the metallurgist will be guided by the total cost of the finished part. The total cost is affected by the steel chosen not only through the first cost of the steel, but indirectly through the influence of the composition on heat-treatment, machining, and rejection costs. By using an alloy steel which will very readily give the required mechanical properties it may be possible considerably to reduce heat-treatment costs because of the less painstaking control demanded and fewer rejections by inspectors. The choice of a costly steel is often justified because it will reduce machining cost. In many cases it is possible for the metallurgist to select a single analysis of steel which, by variation in heat-treatment, will meet the requirements for several different engineering applications within his factory. In this way, problems of purchase, storage and supply may be simplified.

For some applications, data on static mechanical properties are not adequate for selection of material. Reliability under shock loading or

TABLE 5

STEELS OF ABOUT 100,000 TENSILE STRENGTH

Composition								Quench			Draw			Mechanical Properties				
C.	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.26	.20	.50	...	...	...	...	...	870	1600	water	400	750	100,000	....	......	74,000	25	58
.37	.16	.58	...	...	...	...	...	845	1550	do.	565	1050	102,500	80,500	......	87,500	23.5	65
.45	.32	.78	...	...	...	...	...	870	1600	do.	700	1290	100,000	....	......	72,000	28	67
.36	.05	.44	...	.57	...	...	...	815	1500	oil	650	1200	96,000	....	69,000	......	25	60
.34	.15	.87	...	...	.13	...	...	875	1610	do.	600	1110	102,500	....	85,000	......	22	57
.37	.20	.65	3.50	...	...	...	...	800	1475	do.	650	1200	100,000	....	58,000	......	27.5	66
.20	.22	.41	...	...	...	.94	...	830	1525	do.	675	1250	102,000	90,000	......	......	22	64
.32	.21	.63	...	...	...	.83	...	845	1550	do.	675	1250	108,000	....	......	......	23	66
.42	.15	.75	...	1.04	.15	...	...	870	1600	do.	750	1380	103,000	....	97,000	......	30	68
.32	.15	.55	...	.90	...	.37	...	925	1700	do.	760	1400	100,000	....	90,000	......	29	71
.17	.15	.37	2.95	.45	...	...	...	820	1510	do.	540	1000	100,000	....	80,000	......	26	68
.35	.15	.57	1.60	1.18	...	...	...	850	1560	do.	700	1290	115,000	....	77,000	92,000	24	70
.40	.15	.60	1.25	.60	...	...	...	850	1560	do.	595	1100	100,000	74,000	......	......	24.5	71

TABLE 5—(*Continued*)

STEELS OF ABOUT 125,000 TENSILE STRENGTH

Composition								Quench			Draw			Mechanical Properties				
C.	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.20	.30	.75	...	...	...	...	...	900	1650	water	325	615	125,000	....	......	94,000	13	33
.45	.20	.60	...	...	...	...	...	890	1635	do.	205	400	125,000	90,000	......	......	12.5	35
.45	.32	.78	...	...	...	...	...	870	1600	do.	540	1000	125,000	....	......	100,000	23	57
.55	.27	1.25	...	...	...	...	...	?	....	?	?	....	132,000	....	115,500	......	12	48
.47	.11	.60	.51	....	...	...	...	795	1460	oil	705	1300	121,000	....	110,000	......	25	67
.34	.20	.87	...	...	.13	...	...	845	1550	water	565	1050	125,000	....	109,000	......	19	60
.37	.20	.65	3.50	...	...	...	...	800	1470	oil	480	900	125,000	....	110,000	......	18	58
.20	.22	.41	...	...	...	.94	...	910	1670	water	600	1110	125,000	105,000	......	......	17	59
.32	.21	.63	...	...	...	.83	...	845	1550	oil	595	1100	124,000	....	108,000	......	20.5	63
.42	.15	.75	...	1.04	.15	...	...	870	1600	do.	680	1250	125,000	....	......	110,000	24	57
.27	.20	1.01	...	.88	...	.52	...	845	1550	do.	650	1200	125,000	95,000	......	......	20	62
.32	.15	.55	...	.90	...	.37	...	870	1600	water	700	1290	125,000	....	110,000	......	24	66
.37	.15	.55	1.35	.42	...	...	...	800	1470	oil	590	1090	125,000	....	100,000	......	18	58
.40	.20	.63	3.00	.75	...	...	...	790	1450	do.	625	1150	125,000	....	110,000	......	20	61
.32	.12	.46	3.70	1.42	...	...	...	820	1510	air	650	1200	125,000	....	......	103,000	25	67
.29	.14	.62	2.48	...	...	.52	...	845	1550	water	650	1200	121,000	....	116,000	......	22	62
.39	.15	.48	...	1.05	.17	.87	...	870	1600	oil	760	1400	125,000	....	90,000	......	28	66
.70	.26	.62	...	...	...	...	.15	825	1520	water	600	1110	125,000	....	......	105,500	21	55
.70	.26	.62	...	...	...	...	...	825	1520	do.	600	1110	127,000	....	......	110,000	19.5	51

TABLE 5—(*Continued*)

STEELS OF ABOUT 150,000 TENSILE STRENGTH

Composition								Quench			Draw			Mechanical Properties				
C.	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.45	.32	.78	...	...	...	...	...	870	1600	water	250	480	147,000	....	......	107,000	14	36
.57	.20	.65	...	...	...	...	...	830	1525	oil	460	860	145,000	....	97,500	......	16	46
.52	.22	.55	...	...	...	...	...	845	1550	water	300	570	151,000	80,000	......	......	12	40
1.04	.14	.17	...	...	...	...	...	790	1450	do.	540	1000	161,000	137,000	......	......	12	31
.70	.26	.62	...	...	...	...	...	825	1520	water	540	1000	147,000	....	......	129,000	15	39.5
.70	.26	.62	...	...	...	...	.15	825	1520	do.	540	1000	140,500	....	......	122,000	18	48
.34	.01	1.61	...	...	...	...	...	860	1580	do.	425	800	158,000	....	153,000	......	15.5	44.5
.47	.11	.60	...	.51	...	...	...	795	1460	oil	575	1060	150,000	....	135,000	......	19	58
.34	.15	.87	...	...	.13	...	...	845	1550	water	400	750	160,000	....	132,500	......	12	40
.20	.22	.41	...	...	...	.94	...	910	1670	do.	500	930	148,000	110,000	......	......	14	55
.32	.21	.63	...	...	...	.83	...	845	1550	oil	425	800	157,000	....	135,000	......	10	49
.33	.20	.65	3.50	...	...	...	...	800	1470	do.	415	780	150,000	....	140,000	......	16	48
.42	.15	.75	...	1.04	.15	...	...	870	1600	do.	630	1170	150,000	....	......	137,000	17	54
.27	.20	1.01	...	.88	...	.52	...	805	1480	do.	540	1000	150,000	120,000	......	......	16	60
.29	.14	.60	2.48	...	...	.52	...	845	1550	water	595	1100	152,500	....	145,000	......	18.5	60
.20	.20	.40	3.42	...	...	.51	...	845	1550	do.	540	1000	154,000	....	147,500	......	17	48.5
.32	.15	.55	...	.90	...	.37	...	870	1600	do.	605	1120	150,000	....	135,000	......	20	63
.37	.15	.55	1.35	.42	...	...	...	800	1470	oil.	500	930	150,000	....	118,000	......	16	57
.40	.20	.63	3.00	.75	...	...	...	790	1450	do.	520	970	150,000	....	135,000	......	15	55
.40	.15	.40	3.50	1.50	...	...	...	780	1435	do.	540	1000	150,000	....	136,000	......	20	62
.32	.12	.46	3.70	1.42	...	...	...	820	1510	air	545	1010	150,000	....	132,000	......	21	60
.39	.15	.48	...	1.05	.17	.87	...	870	1600	oil	720	1330	150,000	....	125,000	......	22	63

TABLE 5—(*Continued*)

STEELS OF ABOUT 175,000 TENSILE STRENGTH

Composition								Quench			Draw			Mechanical Properties				
C.	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.71	.15	.67	...	...	...	...	...	840	1545	oil	460	860	177,000	....	......	115,500	10	34
1.04	.14	.17	...	...	...	...	...	845	1550	do.	540	1000	175,000	113,000	......	......	11	40
.41	.42	.72	...	...	...	.67	...	870	1600	water	500	930	178,000	....	......	......	14.5	54.5
.32	.21	.63	...	...	...	.83	...	815	1500	do.	540	1000	178,500	....	169,500	......	16	53
.37	.20	.65	3.50	...	...	...	...	800	1470	oil	365	690	175,000	....	165,000	......	13	46
.42	.15	.75	...	1.04	.15	...	...	870	1600	do.	585	1080	175,000	....	......	167,000	11	48
.27	.20	1.01	...	.88	...	.52	...	845	1550	do.	475	890	175,000	145,000	......	......	16	48
.32	.15	.55	...	.90	...	.37	...	870	1600	water	590	1100	175,000	....	......	155,000	17	60
.43	.46	1.24	...	...	...	.73	...	870	1600	oil	550	1020	182,000	....	157,000	......	17	49
.29	.14	.60	2.48	...	...	.52	...	845	1550	do.	540	1000	173,500	....	164,500	......	16.5	57
.37	.15	.55	1.35	.42	...	...	...	800	1470	do.	440	825	175,000	....	140,000	......	14	55
.40	.20	.60	3.00	.75	...	...	...	790	1450	do.	450	840	175,000	....	150,000	......	13	53
.40	.15	.40	3.50	1.50	...	...	...	780	1435	do.	505	940	175,000	....	150,000	......	18	59
.32	.12	.46	3.70	1.42	...	...	...	820	1510	air	465	870	175,000	....	......	157,000	17	55
.39	.15	.48	...	1.05	.17	.87	...	870	1600	oil	700	1290	175,000	....	160,000	......	21	62

TABLE 5—(*Continued*)

STEELS OF ABOUT 200,000 TENSILE STRENGTH

Composition								Quench			Draw			Mechanical Properties				
C.	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.40	.15	.60	...	...	...	...	...	790	1450	oil	315	600	200,000	....	175,000	......	7.5	28
.85	.10	.55	...	...	...	...	...	790	1450	do.	460	860	194,000	....	134,000	......	14	37
1.04	.14	.17	...	...	...	...	...	895	1550	do.	540	1000	199,000	121,000	......	......	10.5	29.5
.70	.26	.62	...	...	...	...	.15	825	1520	water	410	775	199,000	....	......	172,500	12.5	46
.70	.26	.62	...	...	...	...	...	825	1520	do.	410	775	207,000	....	......	180,000	7.5	23
.70	.26	.62	...	...	...	...	...	825	1520	do.	375	705	198,000	....	......	128,000	6.5	5
.70	.26	.62	...	...	...	...	...	825	1520	do.	420	785	197,500	....	......	172,000	8.5	30
.44	.30	1.05	...	...	...	...	...	875	1600	oil	350	660	209,000	....	160,000	......	7	17
.37	.20	.65	3.50	...	...	...	...	800	1470	do.	315	600	200,000	....	188,000	......	12	45
.33	.15	.40	5.00	...	...	...	...	800	1470	do.	330	625	200,000	....	184,000	......	14	57
.40	.20	.55	...	1.00	...	...	...	790	1450	do.	470	880	200,000	....	166,000	......	12	48
.70	.15	.60	...	.50	...	...	...	760	1400	do.	480	900	200,000	....	179,000	......	6	25.5
.38	.35	.71	...	...	...	.37	...	870	1600	water	360	680	208,000	....	185,000	......	12	49
.32	.21	.63	...	...	...	.83	...	845	1550	do.	315	600	209,500	....	165,500	......	11	42.5
.98	.20	.70	...	...	.21	...	...	850	1560	do.	400	750	208,000	....	......	160,000	11.5	33.5
.29	.09	.45	3.41	...	.20	...	...	830	1525	oil	400	750	199,000	....	183,000	......	12	50
.20	.20	.40	3.42	...	...	.51	...	845	1550	do.	315	600	208,500	....	199,500	......	12.5	45.5
.33	.15	.25	4.50	...	...	.58	...	815	1500	do.	430	800	200,000	....	185,000	......	13	52
.29	.14	.60	2.48	...	...	.52	...	845	1550	do.	430	800	195,500	....	188,500	......	13.5	51.5
.50	.07	.92	...	1.02	.20	...	...	900	1650	do.	550	1020	201,000	....	186,000	......	13	45.5
.32	.20	.55	...	.90	...	.37	...	870	1600	water	470	880	200,000	....	185,000	......	14	54
.37	.15	.55	1.35	.42	...	...	...	800	1470	oil	390	735	200,000	....	180,000	......	12	45
.40	.20	.63	3.00	.75	...	...	...	800	1470	do.	380	715	200,000	....	178,000	......	12	51
.40	.15	.40	3.50	1.50	...	...	...	790	1450	do.	430	800	200,000	....	176,000	......	14	53
.32	.12	.46	3.70	1.40	...	...	...	820	1510	air	405	760	200,000	....	179,000	......	15	53
.39	.15	.48	...	1.05	.17	.87	...	870	1600	oil	390	735	200,000	....	180,000	......	15	55
.40	.28	.61	2.52	.84	.20	...	...	810	1490	do.	425	800	207,500	187,500	200,000	......	12.5	52
.39	.28	.71	1.20	.74	.24	...	...	825	1520	do.	425	800	195,000	....	185,000	......	11.5	49
.39	.27	.66	1.28	.68	...	.31	...	825	1520	do.	425	800	200,000	....	170,000	180,000	13	46
.41	.31	.60	2.49	.79	...	.76	...	805	1480	do.	540	1000	200,000	165,000	175,000	180,000	15.5	48

TABLE 5—(*Continued*)

Steels of About 225,000 Tensile Strength

Composition								Quench			Draw		Mechanical Properties					
C	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.40	.29	.77	...	...	...	...	...	870	1600	water	300	570	225,000	....	183,000	......	6.5	17
1.04	.14	.17	...	...	...	...	...	845	1550	oil	315	600	228,000	146,000	......	......	8	20
1.20	.19	.25	...	...	...	...	...	800	1470	do.	345	630	225,000	136,000	......	......	3.5	6
.57	1.22	.61	...	...	...	...	...	825	1520	do.	500	930	219,000	....	204,000	......	5.5	15
.50	.20	.55	...	1.00	...	...	...	790	1450	do.	430	800	230,000	....	197,000	......	10	41
.64	.17	.28	...	1.04	...	...	...	870	1600	do.	400	750	227,500	....	170,000	......	5	13.5
.99	.14	.26	...	...	.32	...	...	850	1560	do.	600	1110	217,000	....	160,000	......	9	26
.41	.42	.72	...	...	...	.67	...	870	1600	water	360	680	223,000	....	190,000	......	12.5	52
.32	.21	.63	...	...	...	.83	...	845	1550	oil	205	400	232,000	....	218,500	......	10	44.5
.37	.20	.65	3.50	...	...	...	...	800	1470	do.	270	520	225,000	....	208,000	......	12	43
.33	.15	.40	5.00	...	...	...	...	800	1470	do.	260	500	225,000	....	200,000	......	13	51
.20	.20	.40	3.42	...	...	.51	...	845	1550	water	205	400	214,500	....	191,500	......	13	45.5
.43	.46	1.24	...	...	...	.73	...	875	1610	oil	400	750	221,500	....	180,000	......	13	49
.40	.20	.60	...	1.00	.18	...	...	900	1650	do.	425	800	226,000	....	200,000	......	10	45
.50	.07	.90	...	1.02	.20	...	...	900	1650	do.	450	840	227,000	....	217,000	......	10	35.5
.32	.15	.55	...	.90	...	.37	...	870	1600	water	250	480	225,000	....	205,000	......	11	47
.40	.40	.62	...	.95	...	.68	...	900	1650	oil	425	800	219,000	....	170,000	......	12	43
.37	.15	.55	1.35	.42	...	...	...	820	1510	do.	315	600	225,000	....	218,000	......	8.5	33
.41	.25	.75	3.41	.18	...	...	...	790	1450	do.	315	600	226,000	189,000	......	196,500	7.5	56.5
.40	.20	.63	3.00	.75	...	...	...	790	1450	do.	330	625	225,000	....	200,000	......	11	48
.41	.15	.40	3.50	1.50	...	...	...	780	1435	do.	360	680	225,000	....	208,000	......	12.5	47.5
.32	.12	.46	3.70	1.42	...	...	...	820	1510	air	200	390	225,000	....	196,000	......	11	44
.41	.41	.64	1.27	.67	...	.83	...	825	1520	oil	460	860	224,000	....	180,000	197,000	12.5	46
.41	.31	.60	2.49	.79	...	.76	...	805	1475	do.	425	800	223,000	190,000	195,000	......	12	40.5
.39	.20	.48	...	1.05	.17	...	.87	870	1600	do.	395	740	225,000	....	205,000	......	11	45
.70	.26	.62	...	...	...	.15	...	825	1520	water	375	705	227,000	....	......	186,000	8.5	23

TABLE 5—(*Continued*)

STEELS OF ABOUT 250,000 TENSILE STRENGTH

Composition								Quench			Draw		Mechanical Properties					
C	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.42	1.50	.86	...	...	...	...	...	860	1580	oil	175	350	259,000	137,000	......	......	4.5	16
.52	2.23	.50	...	...	...	...	...	925	1700	do.	425	800	245,000	....	......	200.000	9	28.5
.50	.20	.55	...	1.99	...	...	...	800	1470	water	400	750	256,000	....	251,000	......	9	30
.32	.21	.63	...	...	...	.83	...	845	1550	do.	205	400	246,500	....	231,000	......	11	41
.50	.59	.42	...	...	...	1.15	...	850	1560	oil	425	800	249,000	....	215,000	......	9.5	31
.37	.20	.65	3.50	...	...	...	...	820	1510	do.	225	430	250,000	....	220,000	......	11	42
.31	.20	.71	...	.95	.15	...	...	850	1560	water	200	390	255,000	....	238,000	......	6.5	26
.50	.07	.92	...	1.02	.20	...	...	830	1525	oil	400	750	260,000	....	240,000	......	8	24
.33	.18	.25	4.50	...	...	.58	...	815	1500	do.	205	400	242,000	....	222,000	......	12	37
.29	.14	.60	2.48	...	...	.42	...	845	1550	do.	205	400	250,500	....	227,500	......	13	41
.40	.15	.65	...	.88	...	.30	...	870	1600	do.	360	680	250,000	....	215,000	......	13	32
.37	.15	.55	1.35	.42	...	...	...	820	1510	do.	205	400	250,000	....	240,000	......	7	22.5
.41	.25	.75	3.41	.18	...	...	...	790	1450	do.	280	535	250,000	187,000	......	......	8	55
.40	.15	.40	3.50	1.50	...	...	...	780	1435	do.	245	475	250,000	....	240,000	......	12	42
.40	.20	.63	3.00	.75	...	...	...	800	1470	do.	260	500	250,000	....	227,000	......	11	43
.39	.20	.48	...	1.05	.17	.87	...	870	1600	do.	260	500	250,000	....	220,000	......	9	35

TABLE 5—(*Continued*)

STEELS OF ABOUT 275,000 TENSILE STRENGTH

Composition								Quench			Draw		Mechanical Properties					
C	Si	Mn	Ni	Cr	V	Mo	Zr	° C.	° F.		° C.	° F.	T. S.	P. L.	E. L.	Y. P.	Elong.	R. A.
.60	.17	.54	...	.88	.19	...	...	900	1650	oil	400	750	273,000	....	249,000	......	8	27
.40	1.10	.86	3.20	...	...	...	...	820	1510	do.	175	350	276,000	140,000	......	......	7.5	25.5
.41	.25	.75	3.41	.18	...	...	...	790	1450	do.	230	445	275,000	176,000	......	......	8	50
.41	.31	.60	2.49	.79	...	.76	...	810	1490	do.	225	430	280,000	165,000	185,000	......	11.5	39
.37	2.50	.52	2.95	...	...	.70	...	860	1575	do.	400	750	275,000	227,000	......	......	7	34
.36	2.42	.51	2.92	...	.12	...	...	870	1600	do.	400	750	262,000	224,000	......	......	7	19.5

against repeated stress may be required, in which case the data from impact or endurance tests must be studied.

In many cases the choice of structural material involves the consideration and careful balancing of many factors and the distinctions made in some of these are of the split-hair variety.

It is not desired to give the impression here that the selection of steel for engineering applications is a simple matter. But, from a broad point of view, it is plain that alloying elements are to a considerable degree capable of interchange or substitution.

It is therefore important to study the possibility of replacing one alloying element by another, in whole or in part. The better this problem is understood, the better fitted the metallurgist becomes to cope with changes in the cost or in the available supply of alloying elements.

Chapter 4.

Molybdenum and Cerium as Alloying Elements.

At present the important alloy steels contain nickel, chromium or vanadium, or various combinations of two or all three of these elements.

Most of the nickel used in steel is mined in Canada. Most of the chromium ores come from New Caledonia, Rhodesia and Asia Minor. Practically all the vanadium is mined in Peru.

Manganese, which is present in all steel and which is sometimes used in such amounts as to make it class as a special alloying element, comes largely from Brazil and (formerly) from Caucasia.

The United States possesses chromium and manganese ores in wide distribution and in fairly large amounts, but, on the whole, in such low-grade deposits that the ores normally do not compete with higher-grade foreign ores.

The iron, carbon and silicon of our alloy steels are domestic—the alloying elements are generally of foreign origin.

The development of a domestic alloying element which can in whole or in part replace or supplement these foreign elements is of obvious importance to American steel makers and users.

Molybdenum is such an element. The United States has the largest potential supply of molybdenum ores of any country in the world, the largest deposit being in Colorado, where there is ore sufficient to produce 100,000 tons of molybdenum. This would suffice for about twenty million tons of molybdenum steel. Other large domestic deposits are known.

Cerium is a by-product obtained in the manufacture of gas mantles. The mantles are made of thoria with about one per cent of ceria. The monazite sand from which the thoria is extracted carries some ten times as much of other rare earth oxides as it does thoria, so that relatively large amounts of oxides of the cerium group, extracted in the process of obtaining thoria, are available. The chief uses are in cored carbons for flaming arcs, and in pyrophoric alloys. These uses are small, and while mix-metal is at present expensive because of the complicated chemical processes required for the treatment of the ore and the extraction of the metals, new uses might decrease the cost by increasing the output.

Monazite comes mainly from India and Brazil, these ores carrying

8 to 10 per cent of thorium oxide. There are extensive domestic deposits in the Carolinas, but as the Carolina ore carries but 3½ to 4 per cent. thorium oxide, domestic ore is seldom mined. Small amounts are shipped from the Pablo Beach, Florida, deposit.

A real tonnage use for the cerium group metals might make it possible for domestic production to be profitable. The refining of monazite into raw materials for gas mantles is largely in the hands of American firms so that the by-products, although chiefly from foreign ores, are a potential American resource.

If either molybdenum or cerium could be used as an alloying element in steel, that fact would be of economic importance. Table 5 has shown that molybdenum can be so used, and so strongly indicates that it may be of such great value as to make it well worth while to examine in detail into its possibilities and peculiarities. Cerium has been tried out so little that the data are lacking from which to draw even a tentative conclusion.

It is difficult to draw final conclusions, even in the case of molybdenum, from the published data, because nearly all of it comes from those interested in the exploitation of deposits of molybdenum ore, who might be prone to put their best foot forward. Moreover, the comparison of tests made by different investigators and under different conditions is less satisfactory than in the case of a single complete set of tests.

Before considering the results of the authors' tests, however, it is necessary to study the data of other observers as given in the literature. This will serve also to point out the gaps in the knowledge of molybdenum steel which the authors' tests were aimed to fill.

Published Data on Molybdenum Steel

The general properties of molybdenum steel were first studied in detail by C. H. Wills and H. T. Chandler, formerly of the Ford Motor Company and were summarized in patents (90) and in booklets (91) (92) put out by the producers of molybdenum and of molybdenum steel. These furnished some of the data which Moore (93) had pointed out as needed when he wrote: "In order to get a steady demand for molybdenum, what is required more than anything else is a definite knowledge of the properties and uses of molybdenum steel . . . Molybdenum steel at the present time is in the same position as vanadium steel was a number of years ago, *viz.*, on trial."

Twenty-five or thirty years ago molybdenum was used in France (94) (95) for increasing the toughness of steel.

In England, Swinden (49) (50) showed a dozen years ago that a steel of 0.32 per cent. C, 0.91 per cent. Cr, 0.46 per cent. Mo had excellent

properties. He predicted the commercial use of steel of that class. The use of molybdenum in a chromium steel was patented in 1895 by Schneider,[96] who specified 0.20 per cent. to 5 per cent. molybdenum and 0.20 per cent. to 3 per cent. chromium.

Chromium-molybdenum steel was used in Liberty engines built by the Ford Motor Company, and to a smaller extent by other makers during the war, and was said by Wood,[97] who had much experience in metallurgical inspection work on those engines, to be the equal of chromium-vanadium steel. It has been used alternately with chromium-vanadium in the Ford car when Wills was with the Ford Company, though it is understood that a plain chromium steel is chiefly used at present.

For some time after the end of the war, there appeared to be little call for and almost no production of, molybdenum steels. But many steel companies and users were experimenting with it and their results have since been published.[15] [95] [55] [98-111]

There is a general agreement among these investigators that the addition of small amounts (0.20 per cent. to 0.75 per cent.) of molybdenum to steel—plain carbon, chromium, nickel or nickel-chromium—makes it possible to obtain, by suitable heat-treatment, either higher elastic limit with the same ductility, or at the same elastic limit, higher ductility and especially a higher reduction of area than in steels without it; that they show greater depth-hardening (*i.e.*, more uniform hardness throughout large sections); that they have a wide range of effective hardening temperatures, variation in which does not greatly alter the mechanical properties (*i.e.*, they are not "sensitive"); and that to secure equivalent softening on tempering with other analogous steels the draw temperatures must be higher.

It is also fairly well agreed that the steel machines as well as other steels of the same strength and hardness; that the steel forges well; and that it readily free itself of scale so that clean forgings result. Several observers, including Mathews,[107] believe that the machining properties are superior to those of other alloy steels. It is at least as free from flaws and other defects as other steels of comparable grades.

The steels can be made either in the open hearth or the electric furnace, using either ferro-molybdenum or calcium molybdate, with practically quantitative recovery of molybdenum. Scrap may be remelted without loss of molybdenum. Molybdenum does not segregate. It does not hinder the absorption of carbon in case-hardening.

It should be noted that molybdenum is not a deoxidizer or scavenger. Kissock [112] shows that molybdenum has less affinity for oxygen than either carbon or iron, which fact is consistent with the quantitative recovery of added molybdenum.

Hence the addition of molybdenum will neither tend to make a dirty steel clean, nor a clean steel dirty. The action of molybdenum therefore

is as an alloying element only, while that of vanadium may be both as a scavenger (113) and an alloying element, as Saklatawalla (114) points out.

While all data available to the authors justifies the statement made above that molybdenum does not segregate, Smith (115) (116) says:

"Molybdenum has undoubtedly a great future before it in the engineering steels. I say advisedly that the chief bar to the rapid advance of its use has lain in a point hitherto neglected by technologists. That point has reference to the subject of dissociation, with which are inextricably wrapped up the phenomena of solution. It is in my mind an undoubted fact that the ideal bath of molten steel should consist of an elementary solution as free as possible from inclusions. If an alloy contains a compound—generally a carbide—undissociable in the temperature zone normal to good steel-making practice the best, (or even reliably constant) results will never be obtained from it. And in this connection ferro-chrome, ferro-vanadium and ferro-molybdenum alloys must especially be scrutinized. One of the greatest sources of complaint in connection with the use of molybdenum has been that it segregates so badly.

"The observed differences of molybdenum have not been due to segregation proper, but rather to manifestations of insolubility and the laws of gravity. The net result is a badly balanced steel with foreign inclusions, difficulty in fabrication, bad test and service results, and a wrongly formed conclusion as to the value of an auxiliary element potent for extreme good." Pokorny (322) seems to agree with Smith.

By choosing a steel of suitable carbon, chromium, and molybdenum content, such a steel can, by suitable variation in heat-treatment, be given such a range of properties as to fill a wide range of needs.

An an indication that molybdenum steels are being found suitable for exacting uses, it may be mentioned that these steels are used extensively in the Wills Sainte-Claire and the Studebaker automobiles, and in Hyatt roller bearings.

There appear to be many metallurgical advantages and few drawbacks to the use of molybdenum as an alloying element. It might be stated here, in anticipation, that in so far as the work of the authors covers the points mentioned above, their results are concordant with the claims made by these various advocates of molybdenum. The properties of molybdenum steels as far as they are given in the literature will be summarized below and some unpublished figures will be given from various sources. Appendix D gives references to data found in the literature, arranged according to the composition of the various molybdenum steels.

Carbon-Molybdenum Steels

Most of the published data refers to chromium-molybdenum steels, very little being given on carbon-molybdenum. Data by users of carbon-molybdenum steels have been supplied by Mr. J. D. Cutter of the Climax Molybdenum Company. These data are shown graphically in Fig. 2.

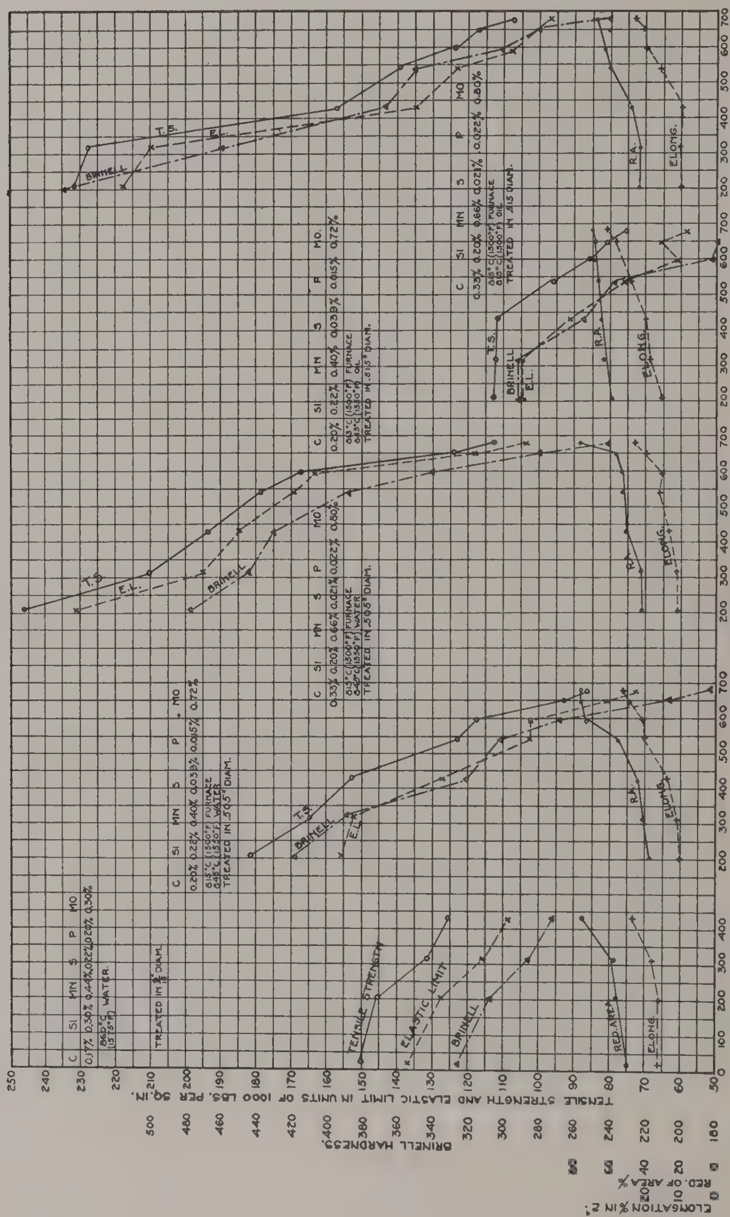


FIG. 2.—Plot of properties of carbon-molybdenum steels.

Further data from Cutter on another carbon-molybdenum steel is given below. The composition was 0.44 per cent. C, 0.88 per cent. Mn, 0.024 per cent. S, 0.024 per cent. P, 0.45 per cent. Si, 0.30 per cent. Mo.

TABLE 6a

Treatment (1¼" inch Round)	Y. P.	T. S.	Elong.	R. A.	Brinell
Normal	91,000	124,000	19	33	228
815° C. (1500° F.) air	86,000	117,000	21	40	217
815° C. (1500° F.) furnace to 540° C. (1000° F.) then air	62,500	96,500	28	51	179
870° C. (1600° F.) air	81,000	119,000	21	37	228
870° C. (1600° F.) furnace to 815° C. (1500° F.) then air	64,000	94,000	25.5	56	174
815° C. air—620° C. (1150° F.) draw	74,000	108,000	21.5	48	210
815° C. air—650° C. (1200° F.) draw	82,000	113,000	19	42.5	222
815° C. air—690° C. (1275° F.) draw	78,000	103,000	24	53	207

Data from McKnight,(263) follow for a steel of 0.32 per cent. C, 0.21 per cent. Si, 0.63 per cent. Mn, 0.83 per cent Mo, annealed one hour at 870° C. (1600° F.), then heat-treated as shown in 0.505 inch diameter, quenching being done from 845° C. (1550° F.) in water.

TABLE 6b

Treatment	E. L.	T. S.	Elong.	R. A.	Brinell	Shore
As forged	98,200	116,000	14	30.5	255	34
205° C. (400° F.) draw	231,000	246,500	11	41	475	65
315° C. (600° F.) draw	165,500	210,000	11	42.5	445	56
425° C. (800° F.) draw	182,500	193,000	13.5	51	430	53
540° C. (1000° F.) draw	169,500	178,500	16	53	385	52
595° C. (1100° F.) draw	163,500	167,500	15.5	52.5	340	50
650° C. (1200° F.) draw	118,000	124,500	20	56.5	270	38
675° C. (1250° F.) draw	103,500	112,500	23	66.5	240	35

The same steel oil-quenched from 845° C. (1550° F.) showed the following properties:

TABLE 6c

Treatment	E. L.	T. S.	Elong.	R. A.	Brinell	Shore
No draw	240,500	253,500	7	3.5	555	63
205° C. (400° F)	218,500	232,000	10	44.5	555	61
315° C. (600° F.)	210,000	220,000	11	43	460	54
425° C. (800° F.)	135,000	157,000	10	49.5	385	49
540° C. (1000° F.)	123,500	134,500	18.5	61	350	47
595° C. (1100° F.)	108,000	124,000	20.5	63	300	36
650° C. (1200° F.)	100,500	117,500	21	61.5	275	33
675° C. (1250° F.)	97,000	108,000	23	66	240	31

Cutter's figures for a 0.20 per cent. C, 0.40 per cent. Mn, 0.72 per cent. Mo steel oil-quenched from 845° C. (1550° F.) are compared below with data from McKnight,(100) on a 0.20 per cent C, 0.70 per cent. Mo steel oil-quenched from different temperatures and with data from French (55) on a 0.20 per cent. C, 0.41 per cent. Mn, 0.94 per cent. Mo steel oil-quenched.

All these were drawn at 540° C. (1000° F.) and were heat-treated in 0.505 inch diameter.

TABLE 6d

	Quenched from: Deg. C.	Deg. F.	Elastic Limit	Tensile Strength	Elong. Per Cent.	R. A. Per Cent.	Izod Foot Pounds
(a)	845	1550	75,400	96,000	26.5	66.7	Not det.
(b)	870	1600	90,400	101,600	22.0	64.2	" "
(b)	925	1700	88,440	102,000	22.5	62.9	" "
(b)	980	1800	89,040	103,500	24.0	65.4	" "
(b)	1040	1900	88,630	100,600	23.0	64.2	" "
(b)	1095	2000	88,800	103,700	22.0	62.3	" "
			Prop. Limit				
(c)	785	1445	57,500	88,700	24.2	52.3	" "
(c)	830	1530	69,500	104,075	18.8	51.4	48
(c)	875	1605	75,000	105,375	21.0	63.0	68
(c)	910	1670	77,000	109,250	22.8	65.5	69
(c)	980	1800	76,000	106,000	23.2	64.8	67

(a) Cutler. (b) McKnight. (c) French.

These figures indicate that this carbon-molybdenum steel not only is not injured by quenching from a high temperature, but requires a fairly high temperature for best results.

Data from French (55) on the normalizing of this steel are given below, and, for comparison, in the last line there are also included data on a 0.20 per cent C, 0.90 per cent. Mn steel, normalized from 900° C. (1650° F.), 1⅛ inch diameter bar, from the British Engineering Standards Committee Report.(117)

TABLE 6e

Normalizing Temp. Deg. F.	Deg. C.	Prop. Limit	Tensile Strength	Elong. Per Cent.	R. A. Per Cent.	Izod Foot Pounds
1445	785	38,500	76,700	35.5	65.4	71
1530	830	21,750	76,700	35.8	67.3	65
1605	875	23,000	76,450	35.8	66.2	57
1670	910	29,650	76,325	33.2	64.0	61
1800	980	32,000	77,300	32.2	62.6	57
		Yield Point				
1650	900	54,000	80,500	34.0	60.0	62

It will be noted that the molybdenum steel is no better than the plain carbon high-manganese steel in the normalized condition, and that it has a low proportional limit, with a minimum at the 830° C. (1530° F.) normalizing temperature.

TABLE 6f

C	Mn	Mo	Size	Water Quenched from ° C.	Drawn at ° C.	E. L.	T. S.	Elong.	R. A.	Izod Foot Pounds	Source
.20	.41	.94	.505	910	400	123,750	169,000	11.5	49.5	44	French
.17	.44	.30	9/16	860	400	110,000	127,000	21	70	..	Cutter
.20	.99	..	1⅛	900	400	75,000	110,000	20	52	45	British Eng. Stds.

If we compare the hardened and tempered steels, as just above, the strengthening effect of the molybdenum in the heat-treated steel is evident. But the data above bring out the fact that in the normalized condition, steel containing molybdenum is generally no better, and may be poorer, than in its absence, while in the heat-treated condition, molybdenum causes improvement.

Chromium-Molybdenum Steels and Chromium-Vanadium Steels

Next in importance to the question of the use of molybdenum without any other alloying elements is its use together with chromium and its effect in comparison with that of vanadium.

In Fig. 3 have been collected data on chromium-molybdenum and chromium-vanadium from various sources. Of these only the last two curves are from data of producers, the rest being from obviously impartial sources.

The "merit index" plotted from the data of Dawe is an expression which is used to approximate the work done in fracture, *i.e.*, the "toughness" of the steel; (99)

$$\text{Merit Index} = \frac{\dfrac{\text{T.S.} + \text{E.L.}}{2} \times \text{Elong.}}{100 - \text{R.A.}}$$

where T. S. = Tensile strength in 1000 pounds per square inch units.
E. L. = Elastic limit in 1000 pounds per square inch units.
Elong. = Elongation in per cent.
R. A. = Reduction of area in per cent.

The superior depth-hardening of both the chromium-vanadium and chromium-molybdenum steels over the plain chromium and the nickel-chromium is shown by Dawe's data (105) for pieces heat-treated in 2 inch square bars. Wills (90) also gives figures showing the depth-hardening properties, and further data on this point from Hunter (102) (103) (104) are shown in Fig. 4. Janitsky (260a) compares the effect of nickel, chromium and molybdenum.

In comparing the chromium-vanadium and the chromium molybdenum steels of Fig. 3, it should be noted that the former is higher in carbon, manganese and chromium, which accounts for the greater strength of the chromium-vanadium steel at the highest draw temperature. The molybdenum steel on which data are given from McAdam,(118) only contained 0.09% molybdenum, which is much lower than the usual percentage. The lower Charpy impact value of the chromium-vanadium steel may be due to its higher carbon content. The endurance figures given by McAdam were the only values for chromium-vanadium or chromium-molybdenum, under true endurance tests, that appeared in the literature up to 1923. They show no appreciable difference between the two steels.

On the curve for the 0.47 per cent. carbon, chromium-molybdenum steel the reduction of area values is low because the specimen tested was flat instead of the standard round piece. The quenching temperature of this steel is not given. That for the 0.50 per cent. carbon, chromium-vanadium steel was probably higher, which may account for its higher strength and lower ductility.

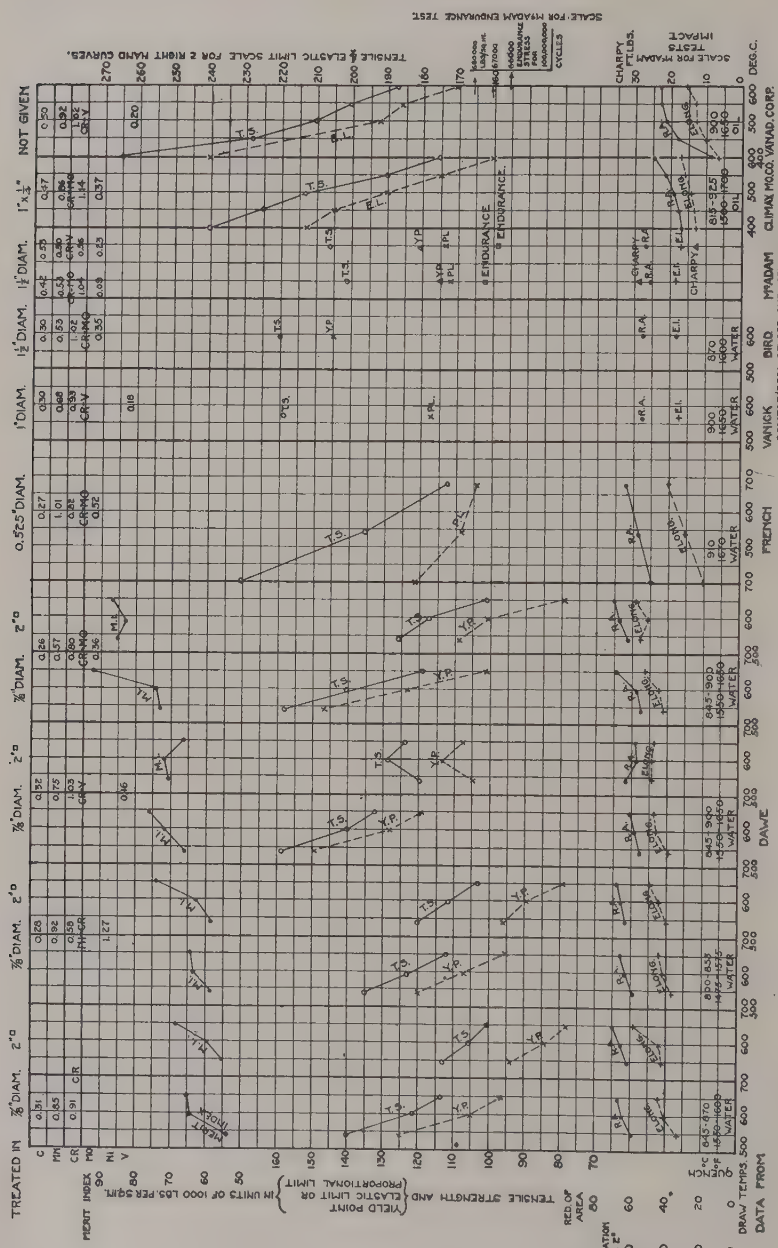


FIG. 3.—Plot of properties of Cr-Mo and Cr-V steels.

On the whole, this collected data would strongly indicate that 0.40 per cent. molybdenum comes very close to giving practically the same results in a chromium steel as that obtained by the addition of 0.20 per cent. vanadium. By increasing the molybdenum up to about 0.80 per cent., the tensile strength may be raised without very great loss of ductility. While the data available on nickel-vanadium vs. nickel-molybdenum steels are not so closely comparable as in the chromium steels, it appears that the relative effect of vanadium and molybdenum is roughly about as found in the chromium steels. By the use of both molybdenum and vanadium in a chromium steel superior results,(91) (95) especially at high draw temperatures, can be obtained over the use of either element alone.

Fig. 4 shows, besides the comparison from Hunter (102) (103) (104) of various steels heat-treated to give the same tensile strength, data interpolated from the table of Griffiths.(33) Data from Schmid (101) and French (55) are plotted to show the lack of effect of change in quenching temperatures on physical properties. Data from French (55) and Mathews (119) are plotted to show that many of the molybdenum steels have the same behavior as an air hardening nickel-chromium steel (117) (compare Fig. 1) in giving a minimum at about 300-350° C. (575-675° F.) in the curve of Izod impact figures plotted against draw temperatures.

Aitchison (10, p. 148; pp. 178-181) shows a somewhat similar minimum, in an air-hardening chromium-nickel steel, an inflection at the same temperature range in an oil-hardening chromium-nickel steel, and a minimum at 400° C. (750° F.) in a 0.31 per cent. carbon steel, and states that this drop in toughness is found in almost all hardened steels.

Grossman discusses this point and shows by experiments on a 0.50 per cent carbon chromium-molybdenum steel that the minimum in the impact draw temperature curve is probably due to retention of a small amount of austenite during quenching and subsequent embrittlement through decomposition of this material when a critical draw temperature is reached. Grossman followed these changes, during quenching and drawing, by dilatometric measurements.(274)

Heat treated castings of chromium-molybdenum steel have given good results, and some data from the Michigan Steel Castings Company (106) are plotted in Fig. 5. Although Giolitti (3) does not deal with molybdenum steels, his comments on the value of heat treated castings in comparison with forgings will be of interest, especially as Giolitti advocates the use of steels with a wide range of temperature between the critical points on heating and on cooling. Molybdenum steels of suitable composition have such a range, that is, they have a tendency to be air-hardening. This effect of molybdenum is quite pronounced, as will be shown in the discussion of the critical ranges. Vanadium does not have such tendency, so in this respect the two elements are not equivalent.

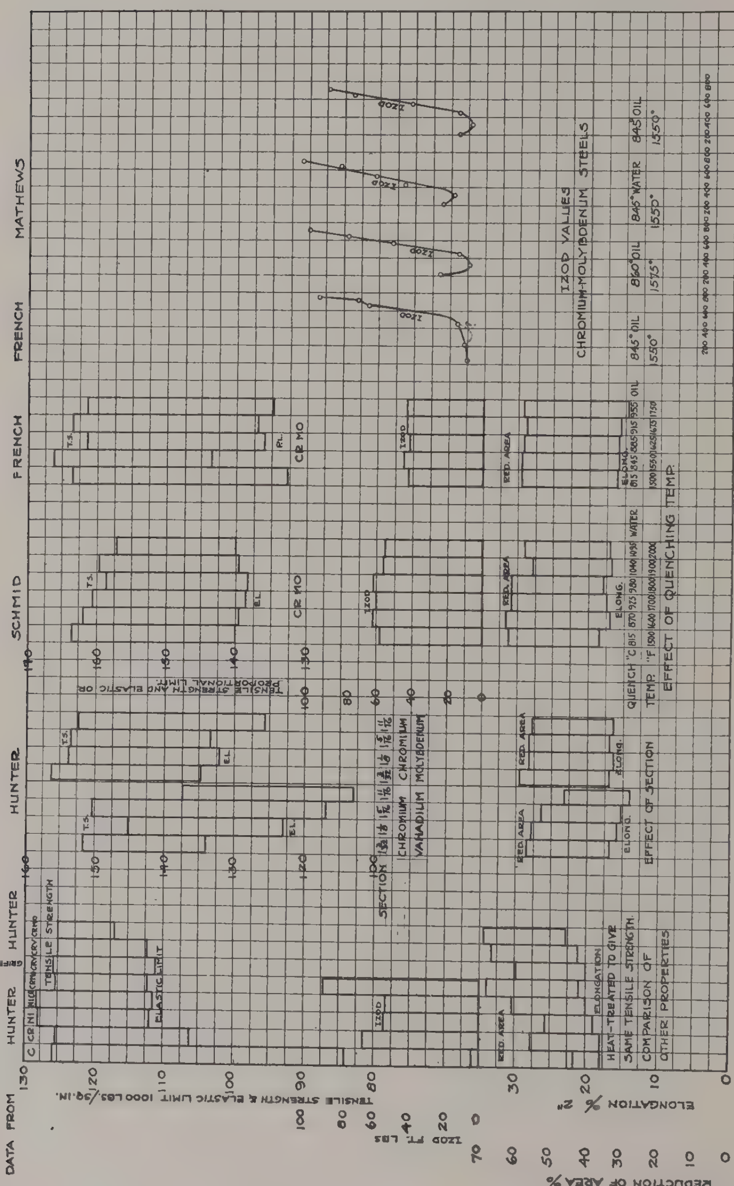


FIG. 4.—Plot of properties of Cr-Mo and other alloy steels.

In a normalized chromium-molybdenum steel the air-hardening tendency may produce poor results as the following data from French [55] reproduced in Table 7 shows:

TABLE 7

Composition: 0.29 Per Cent. C, 1.01 Per Cent. Mn, 0.88 Per Cent. Cr, 0.52 Per Cent. Mo; ½" Inch

Normalized from ° C.	° F.	P. L.	T. S.	Elong Per Cent.	R. A. Per Cent.	Brinell	Izod Foot Pounds
730	1350	85,250	105,600	19.5	64.3	222	76
790	1450	70,500	95,150	23.5	68.5	203	83
815	1500	47,500	103,900	19.5	60.6	232	24
845	1550	29,000	112,200	19.5	49.6	235	23
870	1600	51,500	116,050	18	54.6	243	25

When the normalizing temperature is high enough to produce a tendency toward air-hardening, the proportional limit, ductility and impact value are adversely affected.

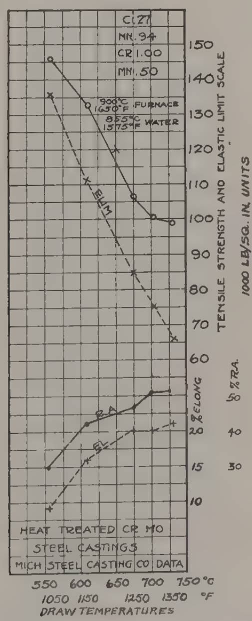


FIG. 5.—Plot of properties of heat-treated Cr-Mo steel castings.

In Fig. 6 are given data from McPherran [120] for heat-treated nickel-chromium, chromium-vanadium and chromium-molybdenum steels and from Spooner [121] for similar steels, normalized, on tests at both normal and elevated temperatures.

In the high temperature tests proportional limit was not determined.

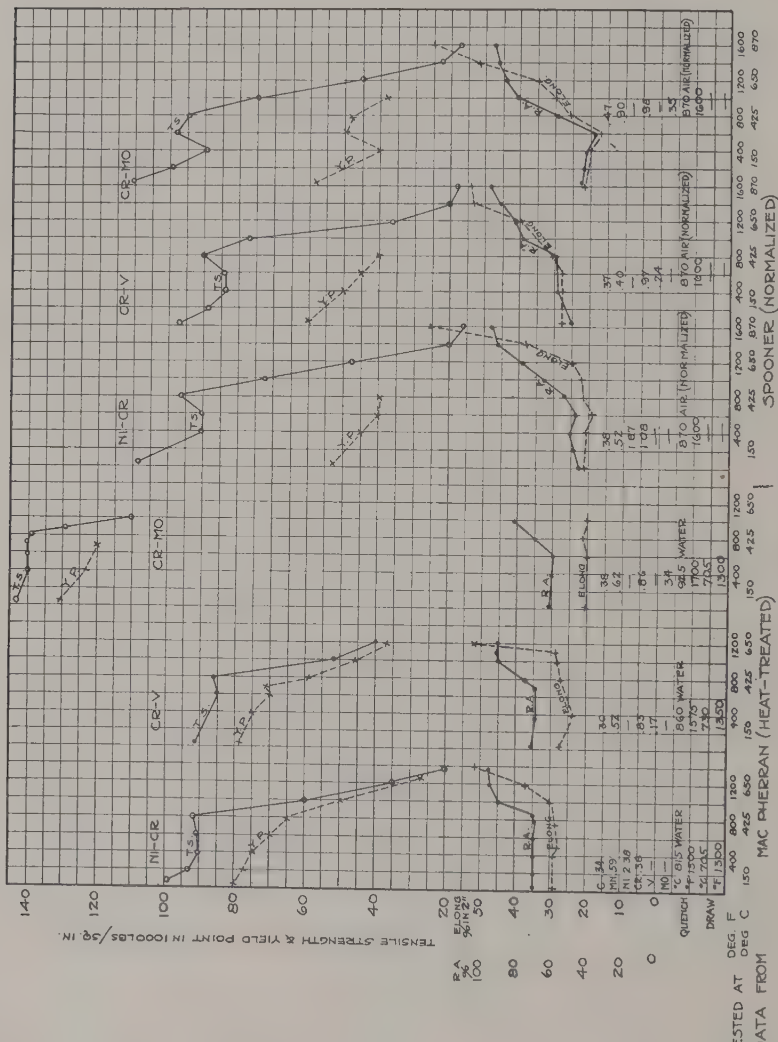


FIG. 6.—Plot of tests at high temperatures of alloy steels.

Spooner's chromium-molybdenum steel was normalized from 870° C. (1600° F.), and notwithstanding its higher carbon content, does not vary widely from French's steel normalized from the same temperature, and shows only such differences from the chromium-nickel and chromium-vanadium steels as would be expected from its carbon content.

These normalized steels do not show a marked yield point, and in comparison by drop-of-beam or divider methods, the normalized molybdenum steel may not show up as poorly as it does on proportional limit test.

French and Tucker (122) examined 27 lots of steel, including plain carbon, stainless (12.75 per cent. Cr), uranium, nickel-uranium, chromium-vanadium die steel, ordinary chromium-vanadium (1 per cent. Cr), and a chromium-molybdenum steel of 0.27 per cent. C, 0.99 per cent. Cr, 0.41 per cent. Mo, at temperatures up to 550° C. (1020° F.). The chromium-molybdenum steel, air-quenched from 845° C. (1555° F.) and tempered at 600° C. (1110° F.) when tested at 550° C. (1020° F.) had both the highest strength (97,500 pounds square inch) and the highest proportional limit (40,500 pounds per square inch) although it contained the lowest carbon of any of the steels that even remotely approached it in strength. The next nearest competitor was the chromium-vanadium die steel normalized from 900° C.(1650° F.) giving at 550° C. (1020° F.) 80,900 tensile strength and 33,000 proportional limit. The normalized chromium-molybdenum steel showed at 550° C. (1020° F.), 70,600 tensile and 23,750 proportional limit. The chromium-vanadium steels were only tested in normalized condition. French and Tucker state that of the factors determined in these tension tests the proportional limit is the chief criterion for service at high temperatures.

Properties of Molybdenum Steels at Low Temperatures

Sykes (276) has compared, in tension at the temperature of liquid air (— 180° C.; — 290° F.), the properties of wires drawn from a 0.30 per cent. carbon steel; from a 0.25 per cent. carbon, 3.5 per cent. nickel steel; and from a 0.30 per cent. carbon, 1.0 per cent. chromium, 0.45 per cent. molybdenum steel. He finds that, of these three steels, whether annealed, quenched, or quenched and drawn at temperatures ranging from 300° C. (570° F.) to 700° C. (1290° F.), the chromium-molybdenum steel is, at liquid air temperature, always the strongest. Except in quenched, untempered specimens the ductility is not adversely affected by lowering the temperature from 25° C. to — 180° C., elongation increasing and reduction of area falling off but little in any of the steels. The molybdenum steel maintains its combination of good strength and good ductility at the temperature of liquid air.

Case-Hardening Properties of Molybdenum Steels

It may be necessary to select the composition of a low carbon, case-hardening molybdenum steel with care. Spaulding [123] finds rapid penetration of carbon into a 0.13 per cent. C, 0.38 per cent. Mn, 0.96 per cent. Cr, 0.48 per cent. Mo steel but finds that the case is not readily refined

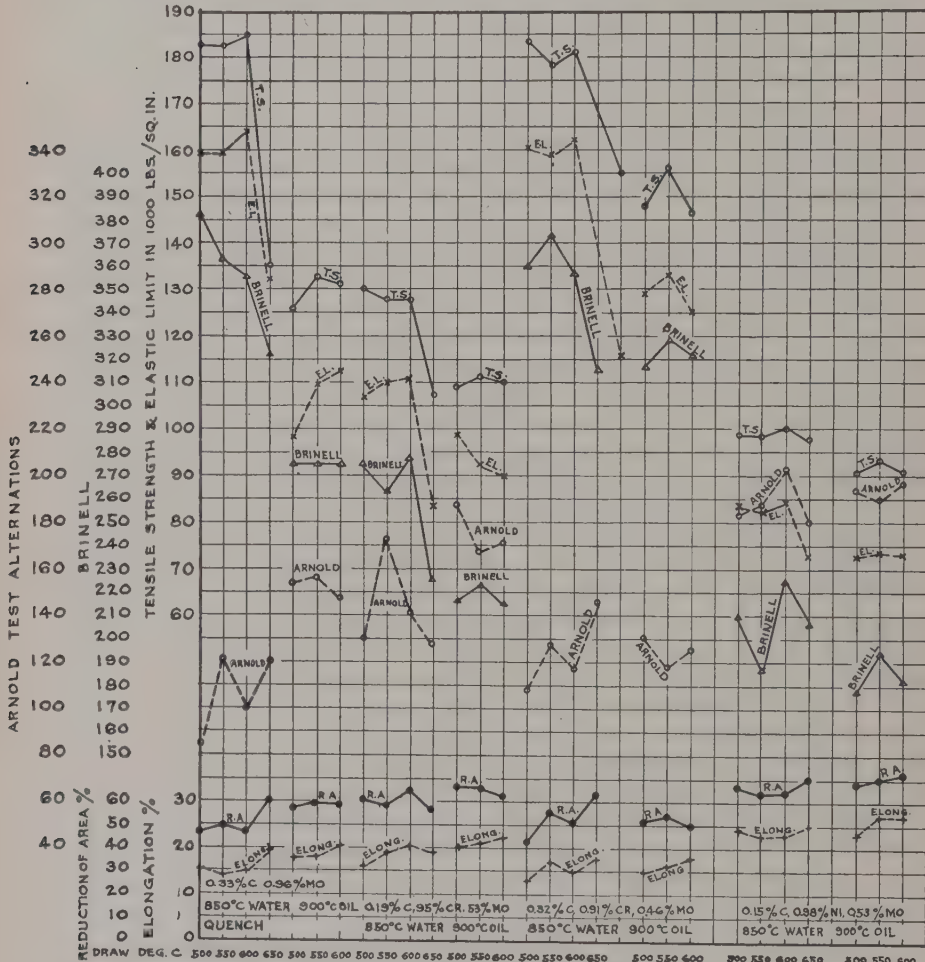


FIG. 7a.—Plot of Swinden's early tests of molybdenum steels.

by double heat-treatment 870° C. (1600° F.) oil; 800° C. (1475° F.) water, and concludes that a good grade of carbon steel would be preferable. A 0.17 per cent. C, 0.73 per cent. Mn, 0.92 per cent. Cr, 0.17 per cent V steel was satisfactory.

Dawe [105] found that a 0.13 per cent. C, 0.40 per cent. Mn, 0.61 per cent. Cr, 0.35 per cent. Mo steel required too high temperatures for double

heat-temperature, and with single heat-treatment did not give a satisfactory core fracture. The latter objection also applied to a steel of 0.19 per cent. C, 0.54 per cent. Mn, 0.70 per cent. Cr, 0.37 per cent. Mo but he considers that a steel of 0.13 per cent. C, 0.38 per cent. Mn, 1.58 per cent. Ni, 0.20 per cent. Mo is promising.

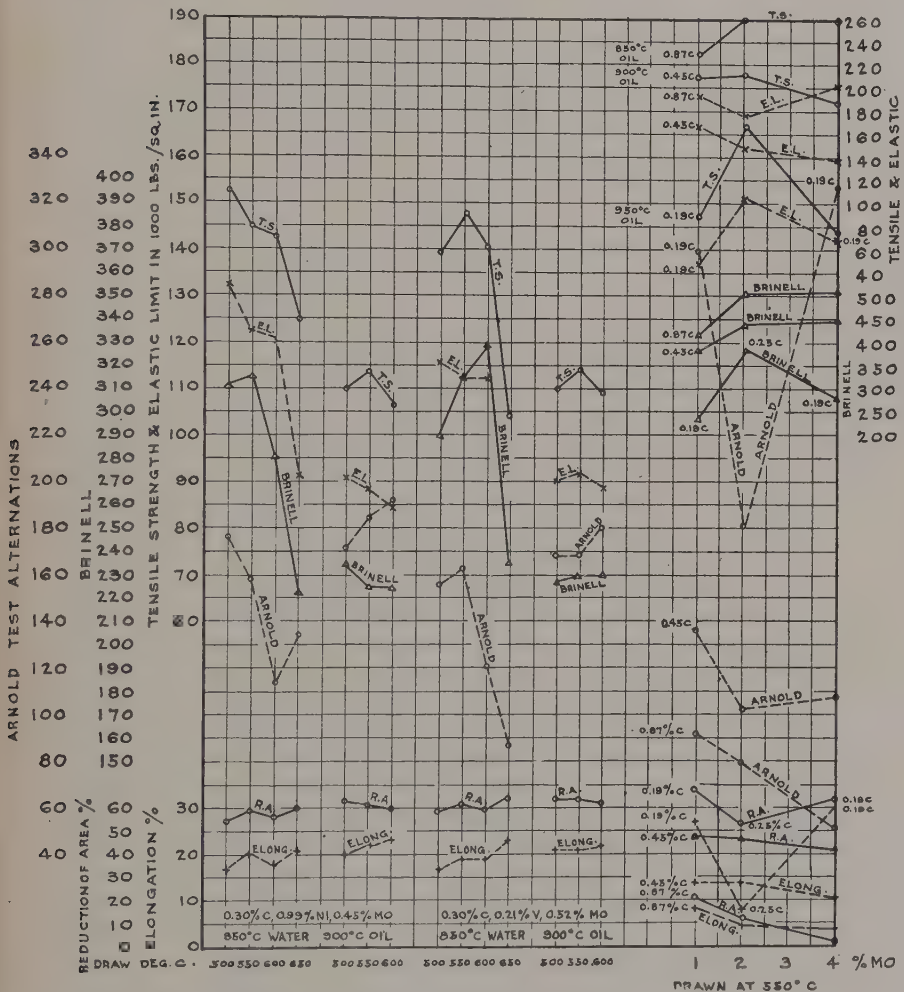


FIG. 7b.—Plot of Swinden's early tests of molybdenum steels.

The temperature limits between which satisfactory results can be obtained on a chromium-molybdenum case-hardening steel are very narrow, while this is not the case with the nickel-molybdenum steel. The latter is claimed to give a greater hardness of case on oil-quenching than any other type of alloy case-hardening steel.

The low carbon molybdenum steels are very ductile, and suitable for deep drawing and stamping in the annealed condition. After forming, they can be given fair mechanical properties by heat-treatment.

Swinden (53) (54) made Arnold alternating impact tests on various molybdenum steels ten years ago, and some of his data on heat-treated steels are plotted in Fig. 7. Further data from Swinden on annealed and normalized steels are given in Table 8. The annealing was done at 950° C. (1740° F.) and the normalizing from 900° C. (1650° F.)

The steels of Table 8, and those of Fig. 7, contained about 0.25 per cent. Mn, 0.07 per cent. Si, 0.03 per cent. S, 0.02 per cent. P, and .03 per cent. Al was added as deoxidizer.

TABLE 8

Swinden's Data on Annealed and Normalized Mo Steels

C	Mo	Cr	Ni	V	Treatment	E. L.	T. S.	Elong. Per Cent.	R. A. Per Cent.	Brin.	Arnold Test
.19	1.03	..	..	..	Ann.	35,000	58,500	36	66	99	336
					Norm.	50,000	68,000	36	75	116	337
.33	.96	..	..	..	Norm.	62,000	90,000	22	52	170	246
.25	2.18	..	..	..	Ann.	31,000	65,000	33	63	116	370
					Norm.	65,000	91,000	30	64	170	282
.19	4.11	..	..	..	Ann.	31,400	63,200	43	72	116	366
					Norm.	63,600	86,000	29	64	170	225
.44	1.05	..	..	..	Ann.	41,000	80,000	25	39	131	210
					Norm.	84,000	117,000	20	49	228	188
.44	2.18	..	..	..	Ann.	43,500	82,000	28	44	143	259
					Norm.	80,000	110,000	23	55	217	212
.49	4.01	..	..	..	Ann.	42,200	77,000	28	52	143	247
					Norm.	81,000	120,000	22	53	228	227
.87	1.02	..	..	..	Ann.	41,000	95,000	5.5	7.5	228	103
					Norm.	102,000	152,000	13	28	302	156
.88	2.19	..	..	..	Ann.	55,000	107,000	19	27	207	126
					Norm.	115,000	160,000	14	33	302	92
.86	4.00	..	..	..	Ann.	46,000	94,000	20	34	179	146
					Norm.	130,000	167,000	14	38	321	111
.19	.53	.95	..	..	Norm.	50,000	72,000	35	68	135	307
.32	.46	.91	..	..	Norm.	69,000	98,000	24	57	226	186
.19	.53	..	.98	..	Norm.	50,000	72,000	33	63	132	320
.30	.45	..	.99	..	Norm.	60,000	86,000	25	59	156	264
.30	.52	..	..	.52	Norm.	62,000	89,500	27	55	168	207

The Arnold tests were made on a ⅜ inch diameter un-notched specimen 6 inches long, which is gripped for 1 inch in a die and struck 3 inches above the die by a plunger which strikes the bar with an impact and then deflects the bar ⅜ inch to one side A similar blow and deflection is then given from the other side. Blows are struck at the rate of 650 alternations per minute. The test is run the same whether a steel of 35,000 pounds per

square inch or one of 160,000 pounds per square inch elastic limit is being tested. The Arnold test is sometimes made [41] with the same deflection but on a 4 inch free length of specimen instead of a 3 inch free length. Figures are only comparable on the same free length. Swinden states that a steel to be used to withstand alternating stress should stand 300 alternations on the Arnold test.[10, p. 99] Only the softest of the molybdenum steels meet this requirement. If the Arnold test is taken as a criterion, it would be concluded that molybdenum steels are lacking in toughness, though this is not the case if the tensile properties or the Izod values of later investigators are considered. The Arnold test cannot be considered a true endurance test, since fracture of a steel assumed to be of good quality takes place in half a minute. As Fig. 7 shows, many of Swinden's results, not only on the Arnold test, but on the ordinary tensile tests appear rather erratic. In fully a third of his specimens the Brinell hardness does not follow the draw temperature.

A recent article by Barton [109] gives data, plotted in Fig. 8, showing the effect of the carbon content of 0.85 per cent Cr, 0.40 per cent. Mo steel at different draw temperatures, both for water and oil quenching. He also gives data on the following: 0.35 per cent. C, 3.00 per cent. Ni, 0.75 per cent. Cr, 0.40 per cent. Mo; 0.25 per cent. C, 2.00 per cent. Ni, 0.75 per cent. Cr, 0.60 per cent. Mo, 0.30 per cent. C, 4.00 per cent. Ni, 0.60 per cent. Mo; 0.40 per cent. C, 1.00 per cent. Cr, 0.20 per cent. V, 0.80 per cent. Mo. He states that a chromium-molybdenum steel has less warpage than other steels of similar tensile strength

The Engineering Division of the U. S. Air Service [111] has compared oil-hardened steels of about 0.27 per cent. carbon, one containing 3½ per cent. Ni, 1½ per cent. Cr; another 1 per cent. Cr, 0.17 per cent. V; and the third 1.2 per cent. Cr, 0.70 per cent. Mo. The steels were electric furnace products made by the Halcomb Steel Company. A very complete series of tests was made, some of the results being plotted in Fig. 9. At the same draw temperatures the tensile strength of the chromium-molybdenum and chromium-vanadium were practically identical, and above that of the nickel-chromium. The nickel-chromium was consequently slightly more ductile. Of the chromium-molybdenum and the chromium-vanadium, the former showed better ductility. At Brinell hardness above 430 the chromium-molybdenum steel showed a lower proportional limit than the other two but at lower hardness the elastic ratios of the three steels were practically identical. The slight differences in torsion and in shear were mostly in favor of the chromium-molybdenum steel. The chromium-vanadium showed the lowest strength in torsion and the chromium-molybdenum the best. Notched-bar single-blow impact tests were made both on the Izod and Charpy machines and each figure plotted is the average of four tests. Up to a 425° C. (800° F.)

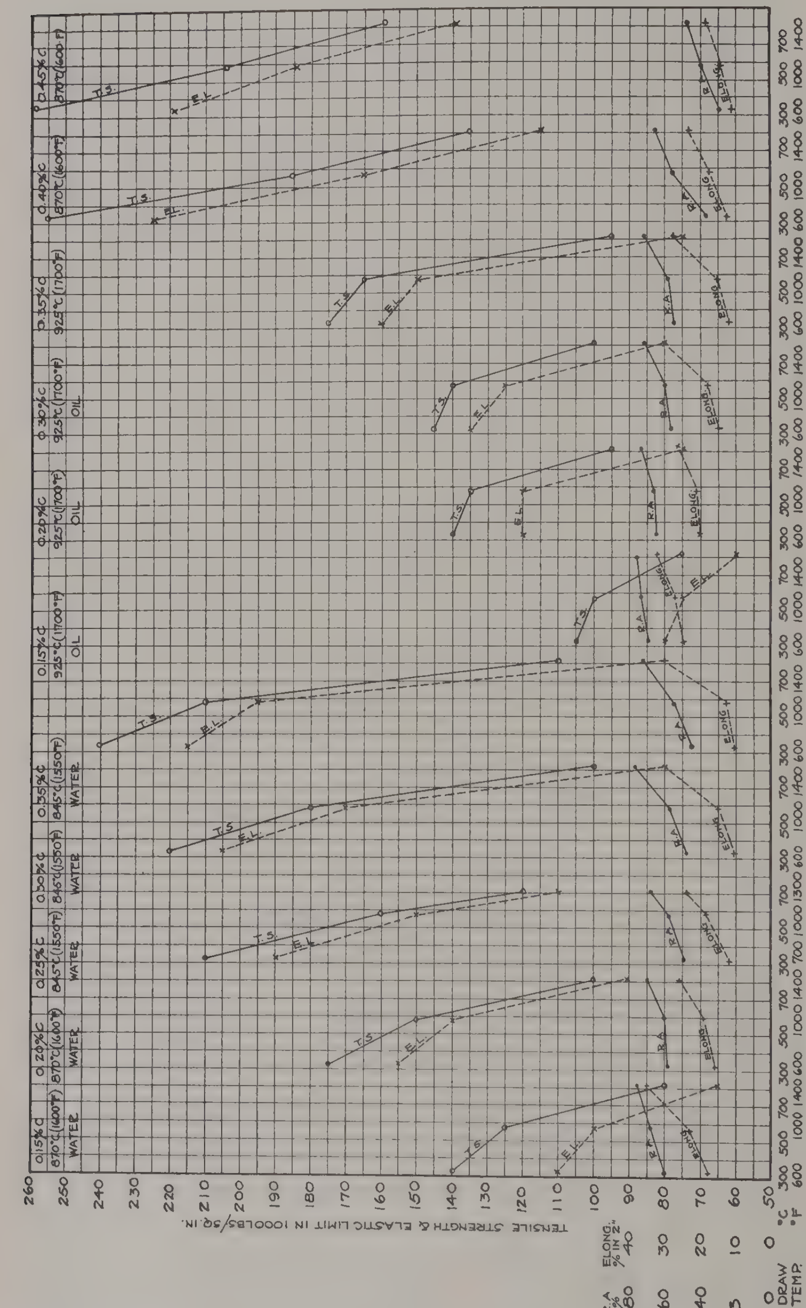


FIG. 8.—Plot of Barton's data on the effect of carbon content in 0.85 Cr 0.40 Mo steel.

draw there was little difference in the impact values, but at higher draw temperatures the chromium-vanadium steel gave decidedly poor results while the nickel-chromium and chromium-molybdenum were equally good. The chromium-vanadium steel gave poor results and the others good ones on both the Izod and Charpy machines.

The depth hardening properties of nickel-chromium and chromium-vanadium steels were compared and the nickel-chromium found decidedly superior. No figures are given for chromium-molybdenum.

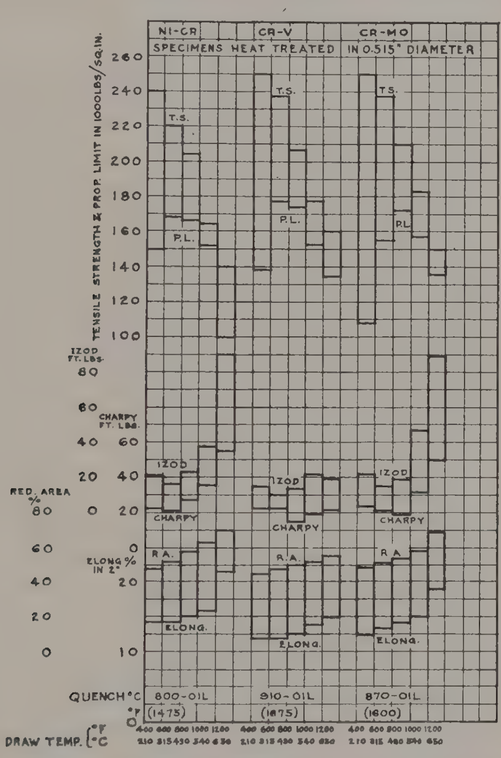


FIG. 9.—Plot of Moore and Schaal's comparison of Ni-Cr, Cr-V, and Cr-Mo steels.

In general, these tests would indicate that the chromium-molybdenum steel was at least the equal of the other two and rather superior to the chromium-vanadium steel on notched-bar impact test.

Tests on a 0.40 per cent. C, 0.69 per cent. Mn, 0.99 per cent. Cr, 0.17 per cent. V steel oil-quenched from 800° C. (1475° F.) and drawn at 650° C.-690° C. (1200-1275° F.) made by P. Longmuir and published in the advertising literature of the European distributors of Vanadium, show a yield-point of 100,000 to 120,000, tensile strength of 120,000 to 132,000, elongation of 22½ to 24 per cent., reduction of area of 66 to 68½ per cent. with Izod values of 74 to 105 foot pounds.

Mr. G. L. Norris (124) suggests that the chromium-vanadium steel used by Moore and Schaal was probably quenched from too high a temperature, 915° C. (1675° F.) and drawn for too short a time (10 min.). If this explanation is correct, it would appear that the impact properties of chromium-vanadium steel are injured by too high a quenching temperature, more than is the case with chromium-molybdenum steel, since Schmid (101) and French (55) (see Fig. 4) respectively find that quenching temperatures up to 1095° C. (2000° F.) do not appreciably reduce the Izod figures on chromium-molybdenum steels of approximately the same carbon and chromium content as the chromium-vanadium steel used by Moore and Schaal.

McAdam (118) compared a steel of 0.42 per cent. C, 1.04 per cent. Mn, 0.09 per cent. Mo, with one of 0.53 per cent. C, 1.46 per cent. Cr, 0.23 per cent. V. These were heat-treated to give respectively 112,500 and 114,000 proportional limit. On Charpy test the molybdenum steel gave 29 foot pounds and the vanadium steel only 13½. But on the Fremont test, another single-blow notched-bar test, the molybdenum steel gave 11 and the vanadium steel 13½ foot pounds. On the impact shear (un-notched) test both steels gave the same figure, 27.6 foot pounds. The vanadium steel had a higher carbon content than the molybdenum steel.

Molybdenum in Other Steels

Sargent (92) presents data on a 5 per cent. nickel steel, on a chromium-vanadium and a nickel-chromium steel, to which molybdenum has been added, which show the same behavior of molybdenum in increasing the ductility for the same strength, or giving greater strength at the same ductility; and in increasing the draw temperature required, as is found in the use of molybdenum in carbon or chromium steels.

The data in Table 9 are unpublished figures furnished by G. L. Norris.

TABLE 9

Nickel-Molybdenum Steel; 0.30 Per Cent. C, 0.29 Per Cent. Mn, 5.01 Per Cent. Ni; 0.62 Per Cent. Mo.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell
800° C.	air	none	221,000	232,500	13	44	...	419
815° C.	air	none	180,000	241,000	12	45	...	...
815° C.	air	315° C.	207,500	221,500	12	53.5	...	...
815° C.	air	650° C.	168,000	169,000	17	57.5	31	421
850° C.	oil	540° C.	172,000	179,000	16.5	53.5	...	364
800° C.	oil	430° C.	181,000	192,000	14	52	...	385
800° C.	oil	540° C.	165,500	175,000	16.5	54	...	351
800° C.	oil	650° C.	104,000	136,000	21.5	54.5	...	267
800° C. 750° C.	oil water	450° C.	186,000	189,000	14.5	54	...	382

TABLE 9—(*Continued*)

Nickel-Chromium-Molybdenum Steel; 0.50 Per Cent. C, 0.59 Per Cent. Mn, 1.01 Per Cent. Ni, 0.74 Per Cent. Cr, 0.75 Per Cent. Mo.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell	Shore
700° C.	air	none	114,000	115,000	19	60	...	...	...
830° C.	do.	315° C.	232,000	253,000	....	....	...	...	...
do.	do.	600° C.	197,000	216,000	13	42	...	...	...
do.	do.	650° C.	197,000	206,000	13	46	21	387	...
do.	do.	700° C.	126,000	142,000	20	58.5	...	...	...

Chromium-Molybdenum-Vanadium Steel; 0.41 Per Cent. C, 0.62 Per Cent. Mn, 1.07 Per Cent. Cr, 1.01 Per Cent. Mo, 0.20 Per Cent. V, 0.09 Per Cent. Cu.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell	Shore
annealed			59,000	90,500	26	58	...	170	...
750° C.	oil	430° C.	65,000	90,500	25	63	...	171	...
815° C.	do.	do.	187,000	218,000	8	33.5	...	447	...
875° C.	do.	do.	211,000	233,000	10	41	...	465	...
925° C.	do.	do.	212,000	238,000	9	39	...	477	...
985° C.	do.	do.	201,000	240,000	10	44	...	477	...
1040° C.	do.	do.	205,000	242,000	9	35	...	477	...
925° C.	do.	95° C.	....	236,000	1	4	...	...	...
do.	do.	205° C.	....	277,000	3.5	6	...	...	...
do.	do.	315° C.	....	268,500	10	32	...	...	...
do.	do.	430° C.	220,000	253,000	10	37	...	...	...
do.	do.	540° C.	210,000	225,000	13	42	...	...	...
do.	do.	650° C.	195,000	208,000	14	47	...	...	...
do.	do.	760° C.	97,500	147,000	15.5	40	...	...	...

Chromium-Nickel-Molybdenum-Vanadium Steel; 0.41 Per Cent. C, 1.03 Per Cent. Cr, 0.70 Per Cent. Mo, 0.38 Per Cent. Ni, 0.45 Per Cent. V.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell	Shore
900° C.	oil	315° C.	225,000	250,000	10	45	...	...	...
do.	do.	540° C.	210,000	220,000	12.5	54	...	...	...
850° C.	do.	650° C.	139,000	146,000	17	53.5	50	285	...

Chromium-Molybdenum-Vanadium Steel; 0.28 Per Cent. C, 0.70 Per Cent, Mn, 1.19 Per Cent. Cr, 0.74 Per Cent. Mo, 0.20 Per Cent. V.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell	Shore
800° C.	air	none	109,000	152,000	17	40	...	286	...
775° C.	salt at	345° C.	110,000	135,000	21	60	...	265	...
860° C.	do.	430° C.	132,000	170,000	11.5	29	...	314	...
775° C.	do.	375° C.	112,000	125,000	23.5	65	...	241	...
775° C.	do.	625° C.	108,000	121,000	22	60	...	237	...
860° C.	oil	485° C.	190,000	204,000	13	48	...	390	...
860° C.	do.	600° C.	179,500	188,500	14	51	...	382	...
860° C.	do.	700° C.	120,000	125,000	20.5	60	...	242	...
875° C.	do.	650° C.	202,000	206,500	14	50	...	418	...

TABLE 9—(*Continued*)

Chromium-Molybdenum-Cobalt Steel; 0.65 Per Cent. C, 0.12 Per Cent. Mn, 2.16 Per Cent. Cr, 3.05 Per Cent. Mo, 1.33 Per Cent. Co.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell	Shore
940° C.	oil	315° C.	175,000	266,500	...	...	...	512	73
do.	do.	430° C.	224,500	246,000	...	...	...	512	73
do.	do.	540° C.	....	289,000	2.1	...	...	555	73
1060° C.	do.	430° C.	186,000	217,000	2.3	...	...	600	98
1140° C.	do.	430° C.	....	186,500	1.2	...	...	600	96
1060° C. 920° C.	do. do.	540° C.	163,000	295,000	2.9	...	...	555	95
940° C. 850° C.	do. do.	315° C.	216,500	365,000	1.2	...	...	555	91
940° C.	salt at	650° C.	167,500	206,000	66.8	...	...	418	80

Nickel-Molybdenum Steel*; 0.29 Per Cent. C, 0.15 Per Cent. Si, 0.60 Per Cent. Mn, 2.48 Per Cent. Ni, 0.52 Per Cent. Mo.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell	Shore
as forged			108,500	124,000	12	28.5	...	255	38
845° C.	water	205° C.	206,000	261,000	12.5	46	...	460	64
do.	do.	315° C.	196,000	224,500	12	47	...	445	63
do.	do.	425° C.	189,000	203,000	12.5	50	...	385	59
do.	do.	540° C.	158,500	168,500	16	55.5	...	365	52
do.	do.	595° C.	145,000	152,500	18.5	60	...	320	48
do.	do.	650° C.	116,000	121,000	22	62	...	260	42
do.	do.	675° C.	102,500	114,000	23	65.5	...	255	41
do.	oil	none	236,000	268,000	10.5	31.5	...	600	68
do.	do.	205° C.	227,500	250,500	13	41	...	530	62
do.	do.	315° C.	198,000	254,000	12.5	42.5	...	530	61
do.	do.	425° C.	188,500	195,500	13.5	51.5	...	420	52
do.	do.	540° C.	164,500	173,500	16.5	57	...	385	50
do.	do.	595° C.	124,500	140,000	20.5	60	...	320	37
do.	do.	650° C.	96,500	122,000	23	57.5	...	255	32
do.	do.	675° C.	99,500	118,000	23	62	...	250	30

* Data from Mr. C. McKnight, Jr.

Nickel-Molybdenum Steel*; 0.20 Per Cent. C, 0.20 Per Cent. Si, 0.40 Per Cent. Mn, 3.48 Per Cent. Ni, 0.51 Per Cent. Mo.

Quench	Medium	Draw	E. L.	T. S.	Elong.	R. A.	Izod	Brinell	Shore
as forged			94,000	110,000	13	23.5	...	240	32
845° C.	water	205° C.	191,500	214,500	13	45.5	...	445	56
do.	do.	315° C.	156,000	181,000	12.5	51.5	...	385	50
do.	do.	425° C.	156,500	163,500	14	55	...	365	48
do.	do.	540° C.	147,500	154,000	17	48.5	...	340	48
do.	do.	595° C.	141,000	145,000	18	57	...	330	47
do.	do.	650° C.	105,000	113,500	21	57	...	240	33
do.	do.	675° C.	94,500	113,000	25	60.5	...	230	33
do.	oil	none	193,500	212,500	12.5	45.5	...	475	56
do.	do.	205° C.	194,500	209,000	12	47.5	...	460	55
do.	do.	315° C.	200,000	208,500	12.5	46	...	445	54
do.	do.	425° C.	158,500	166,500	13	53	...	375	48
do.	do.	540° C.	144,500	153,500	16.5	59.5	...	340	45
do.	do.	595° C.	123,000	132,000	21	62	...	300	36
do.	do.	650° C.	88,000	117,500	24.5	62	...	255	31
do.	do.	675° C.	87,000	113,500	24.5	59.5	...	240	30

* Data from Mr. C. McKnight, Jr.

Liberty Motor crankshaft tests are given [91] as follows, after suitable heat-treatment in each case:

C	Mn	Si	Cr	Ni	Mo	E. L.	T. S.	El.	R. A.	Brin.	Izod
.40	.65	.15	.80	2.00	nil	130,000	144,500	17	54	307	46
.33	.50	.17	1.00	3.25	nil	117,000	135,000	19.5	57	270	61
.26	.60	.15	.80	3.00	.40	130,000	142,000	20.5	65	303	67

The values on the molybdenum steel are the average of 30 tests chosen at random. The Izod values of the molybdenum steel range from 46 on one sample showing a little higher strength and lower ductility than the rest, to 82 on another of almost the average values and differing only in having 0.52 per cent silicon.

Mathews [125] gives the following on Liberty Motor crankshafts, presumably water-hardened from 840° C. (1540° F.) drawn at 570° C. (1050° F.).

C	Cr	Ni	Mo	E. L.	T. S.	El.	R. A.	Brin.	Izod
.34	.76	3.43	nil	122,500	142,750	18	57	311	56
.30	.86	3.05	.53	135,700	149,000	19	63	302	51
.50	.88	1.90	nil	124,300	140,600	20	56.5	302	49

A detailed study of the effect of molybdenum in nickel steels was recently made [110] by the Woolwich Arsenal, England. Specimens were cut from large forgings and the properties were studied, both after heat-treatment in the mass, and on 1″ x 1¾″ x 5″ specimens cut out before heat-treatment. Data on some of the smaller specimens are given in Fig. 10. It should be noted that these specimens were all cut out transverse to the direction of forging, that the test length dimensions on the tensile specimens were 2″ x 0.564″, that the proportional limit was determined by the Ewing extensometer, the yield-point taken as the stress giving 0.004″ permanent extension in 2″, and that the Izod test-piece used was the British Engineering Standards Association type 10 mm. x 10 mm. with a V notch 2 mm. deep and 0.25 mm. radius at the base. All Izod values are the average of three or more closely agreeing tests.

The outstanding point of the tests summarized in Table 10 and plotted in Fig. 10, in which tests were made by water quenching after the draw, (plotted on the left and marked "W") and also by slow cooling at the rate of 0.3° C. per minute (plotted on the right and marked "S"), is that all of the five nickel-chromium steels having a tensile strength of over 110,000 pounds per square inch showed "temper brittleness," *i.e.*, a low Izod test on a slow cooling after the draw. Three of the five (the three containing the highest amounts of nickel plus chromium) also showed poor ductility in the tensile test after slow cooling. The nickel-chromium steels containing molybdenum show a better all-around combination of properties than do those without it.

The report states that a nickel-chromium steel containing 0.30 per cent. C, 2.25 per cent.-2.50 per cent. Ni, 1.0 per cent. Cr should be an improvement over the compositions tried but it further states: "Results obtainable

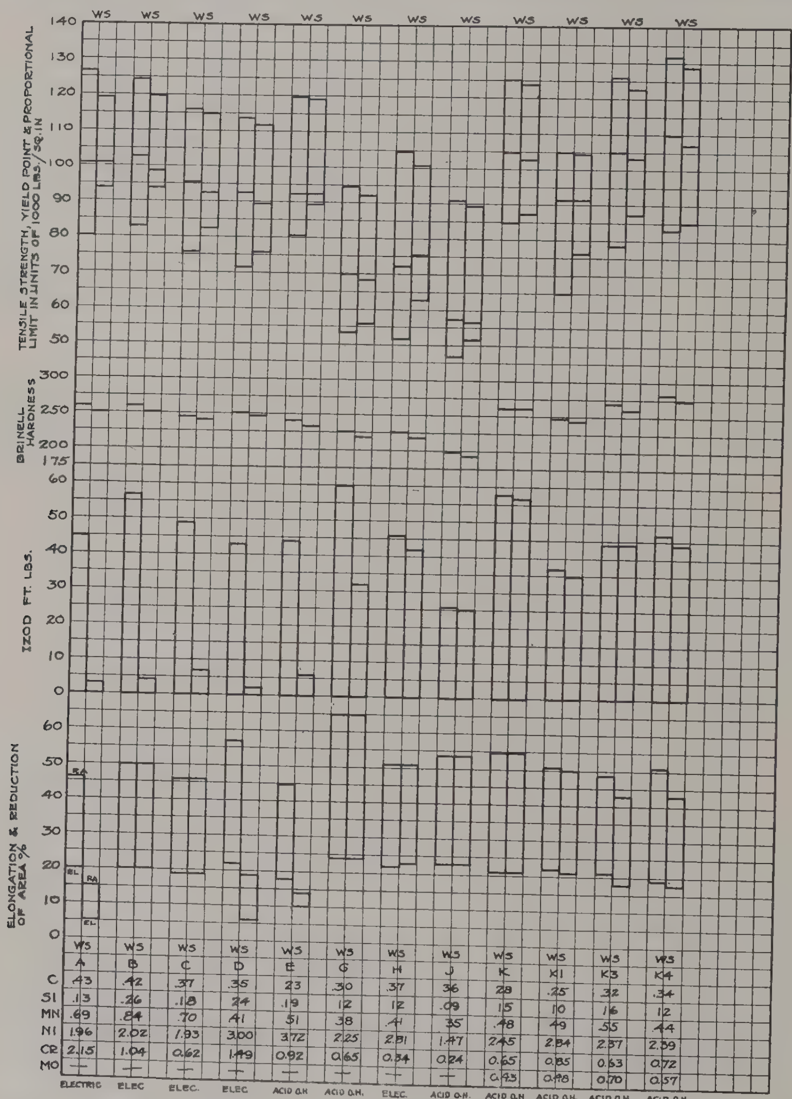


FIG. 10.—Plot of Woolwich Arsenal tests of Ni-Cr and Ni-Cr-Mo steels.

with this composition are, however, unlikely to be better, even if as good as those given by the steel of 0.28 per cent. C, 2.45 per cent. Ni, 0.65 per cent. Cr, 0.43 per cent. Mo in which some of the chromium of the above type is replaced by about 0.5 per cent. of molybdenum." The advantages

TABLE 10

No.	Process	Composition C	Si	Mn	S	P	Ni	Cr	Mo	Size (Inches) I. D. Inch	O. D. Bottom	O. D. Top	Anneal ° C.	Anneal ° F.	Heat Treatment Oil Quench ° C.	Oil Quench ° F.	Draw ° C.	Draw ° F.
A	Electric	.43	.13	.69	.021	.027	1.96	2.15	..	5.5	12.75	9.	900	1650	850	1560	660	1220
B	do.	.42	.26	.84	.010	.032	2.02	1.04	..	5.5	12.75	9.	900	1650	850	1560	660	1220
C	do.	.37	.18	.70	.012	.033	1.93	0.62	..	5.5	12.75	9.	900	1650	850	1560	660	1220
D	do.	.35	.24	.41	.020	.038	3.00	1.49	..	5.5	12.75	9.	900	1650	850	1560	660	1220
E	A. O. H.	.23	.19	.51	.038	.031	3.72	0.92	..	10.	21.5	19.	835	1535	815	1500	650	1200
G	A. O. H.	.31	.23	.46	.033	.037	2.34	0.57	..	7.25	16.5	12.75	815	1500	805	1475	625	1150
H	Electric	.37	.12	.41	.028	.023	2.81	0.34	..	2.5	7.5	5.87	815	1500	815	1500	625	1155
J	A. O. H.	.36	.09	.35	.042	.036	1.47	0.24	..	.....	6.5	5.75	900	1650	900	1650	540	1000
K_1	A. O. H.	.25	.10	.49	.040	.035	2.84	0.85	.48	.....	9.75	7.	925	1700	845	1550	620	1150
K_2	A. O. H.	.29	.14	.48	.032	.026	2.47	0.64	.47	32.	47.75	43.5	845	1550	835	1530	650	1200
K_3	**A. O. H.**	**.32**	**.16**	**.55**	**.034**	**.028**	**2.37**	**0.63**	**.70**	15.5	32.5	23.75	870	1600	845	1550	635	1175
K_4	A. O. H.	.34	.12	.44	.030	.030	2.39	0.72	.57	18.5 24.5	47.87	27.25	870	1600	845	1550	595	1100

TABLE 10—(*Continued*)

No.	P. L. Range		Y. P. Range		T. S. Range		Elong. Range		R. A. Range		Izod Range	
A	83,000 to	92,000	87,500 to	98,000	108,000 to	117,000	16 to	24	31 to	55	34 to	14
B	33,600	83,000	51,500	91,000	66,500	115,500	4 *	24	22 *	62	64 *	23
C	60,500	74,000	67,000	84,000	86,500	117,500	3	21	15	52	39	34
D	72,000	83,000	87,000	91,500	112,000	114,000	19	20	39	43	15	11
E	67,000	......	81,500	85,000	102,000	105,500	16	19	32	49	45	13
G	45,000	62,500	64,500	76,000	87,200	102,500	14	25	23	57	57	16
H	42,500	60,500	53,700	74,000	81,000	108,500	4	24	22	51	39	25
J	49,300	......	53,700	......	89,000	....	21	..	42	..	15	..
K_1	69,500	71,500	84,500	87,000	108,500	110,000	17	18	41	50	30	26
K_2	83,000	89,500	92,500	103,000	114,000	124,000	18	19	49	52	31	27
K_3	89,500	101,000	102,000	112,000	124,000	130,000	18	19	38	49	46	42
K_4	99,000 **	110,000	111,000	136,000	129,700	152,500	16	19	37	50	41	19 **

* On a 66,500 pound per square inch tensile specimen. White spots noted in fracture of specimen.

** On a 149,500 pound per square inch tensile specimen. K_4 was a large forging; draw temperature at top 653° C. (1200° F.); at bottom 595° C. (1100° F.). The high-tensile-strength, low-Izod-value specimens were from the bottom.

of this steel over any of the nickel-chromium steels examined were very pronounced in several respects:

(a) Its properties in the oil-hardened and tempered condition were very uniform and were unaffected by a considerable variation in initial temperature and rate of cooling in oil.

(b) Good elongation was combined with a high yield point and the fall of hardness with increase of tempering temperature was gradual.

(c) The steel appeared to be quite unsusceptible to temper brittleness.

The tests on specimens from large forgings, heat-treated in the mass showed that the effect of section in oil-hardened steels was slight in the case of two steels (A and B) which were high in carbon, nickel and chromium, and in the case of all the molybdenum steels (Type K) while the other steels were either somewhat affected (D, E, and C) or notably so (G, H, and J). Only one of the nickel-chromium steels, the one highest in carbon and in chromium of the series, was found fully air-hardening at the center of a 3 inch diameter rod. A good deal of work on the study of temper brittleness of the nickel-chromium steels, by re-tempering at various temperatures, and on the critical ranges of the steels is included in the report, and many micrographs are given. Fig. 11 of this book shows some of the critical point curves.

While the tests on the steels as heat-treated in the mass in large forgings are not entirely comparable, due to differences in the dimensions of the forgings and in annealing, quenching and drawing temperatures, the results given above show that the steels containing molybdenum gave a better combination of strength, ductility and Izod value than the steels that did not contain it.

The phenomenon of temper brittleness is so obscure and its causes so poorly understood that it would be unsafe to state dogmatically that the substitution of some chromium of a nickel-chromium steel by molybdenum will avoid temper brittleness. Of two nickel-chromium steels of exactly the same composition one may be temper brittle and the other may not, and it might be that only nickel-chromium-molybdenum steels which did not happen to show the phenomenon were tested.

Lorenz (273) gives some data on the addition of 0.40 per cent. molybdenum to a steel of 0.40 per cent. to 0.45 per cent. C, 1.80 per cent. Ni, 0.75 per cent. Cr. for use in heat-treated steel castings. He points out that, without molybdenum, this steel requires water quenching but with molybdenum it is air-hardening.

Johnson (126) has used molybdenum in nickel-silicon steels with good results but says that the good properties may not be due to molybdenum. Burgess and Woodward (162) made a few tests on nickel-silicon steels carrying molybdenum, which were quenched in oil and drawn at but one temperature, 175° C. (350° F.) and concluded that it was probable

that the steels would have been superior had the molybdenum been omitted. Detailed data on steels of this type will be given in Chapter 11.

Besides its use in ordinary alloy steels, molybdenum has been used in high speed steels, but molybdenum is sufficiently volatile so that in the percentages used in tool steel it volatilizes from the surface in rolling, forging and heat-treating, and the action of molybdenum does not appear to be as dependable in high steels as that of tungsten. Nor is molybdenum in any way equivalent to the vanadium used in modern high-speed steels.

A cobalt-molybdenum high-speed steel, containing no tungsten, gave the poorest results in cutting tests of any of the 16 steels tested by d'Arcambal.[57]

French and Strauss [58] found no advantage in the presence of a little molybdenum in high-speed steel.

Molybdenum sometimes enters into Stellite [127] and into various high cobalt-chromium tool and die steels.[128] It is sometimes used in valve steels and in various noncorroding alloys and non-oxidizing alloys. These uses do not call for extended comment in connection with the present investigation, nor does the use in cast iron,[129] which Smalley [130] considers very promising.

Molybdenum is used in rolls [131] [272] such as those for blooming mills, etc., and in forging dies. These various uses indicate that the effect of molybdenum is shown in almost any grade or composition of steel. Practically the same results obtained with any particular molybdenum content could probably be obtained without it, by proper proportioning of other alloying elements and with a heat-treatment correctly chosen for the new composition.

Sometimes the molybdenum steel and sometimes some other composition may be cheaper per pound. The ability of molybdenum steels to stand, without damage, over-heating before quenching is also found, to perhaps a slightly less degree, in chromium-nickel and in vanadium steels. The depth hardening property of molybdenum steel is quite definitely greater than that of the corresponding vanadium steel and probably equal to if not greater than that of comparable chromium-nickel steels.

The free-scaling properties in forging and the machining properties of molybdenum steels appear as strong points in its favor. The high temperature required for drawing molybdenum steel makes control of the heat-treating process less difficult when a tensile strength of 125,000 pounds, or above is sought in the common molybdenum steels. If 100,000 pounds or less is sought, the control may not be so easy because the slope of the strength, draw-temperature curve is steeper below 125,000 pounds.

McKnight [100] and Schmid [101] point out that any alloy steel manufacturer can secure a license to produce chromium-molybdenum steel under "trivial" royalties.

The value of molybdenum as an alloying element is not so much in allowing the metallurgist to produce results that he can get with no other steels, but in giving him an added means of producing desired results. Under some market conditions, it is quite possible to produce the results more cheaply with molybdenum.

Dawe states that chromium-molybdenum steel has been produced and sold at a lower price than an equivalent chromium-vanadium steel. At present prices (Jan., 1925) ferro-molybdenum is quoted [a] at $1.80 to $2.00 and ferro-vanadium at $3.25 to $4.00 per pound of contained element. On the basis of cost as well as of mechanical properties the two appear fairly interchangeable in a heat-treated alloy steel. Nickel is quoted at 31 to 32 cents per pound and high carbon ferro-chromium at 10¾ to 11 cents per pound of contained chromium.

Hot rolled bars were quoted as follows in cents per pound in Jan., 1925.[b]

3½ per cent. Ni	4.75
1¼ per cent. Ni, .6 per cent. Cr	3.65
3½ per cent. Ni, 1½ per cent. Cr	7.50–7.75
1 per cent. Cr, .18 per cent. V	4.25
1 per cent. Cr, .35 per cent. Mo	4.25
.60 per cent. Cr, .20 per cent. Mo	3.75

Molybdenum steels are therefore no more expensive than the other alloy steels for which they might be substituted.

One of the leading producers of molybdenum states that the cost of molybdenum ore and hence of ferro-molybdenum will almost certainly be materially decreased in the very near future, probably by the time this book is in the reader's hands. While no prediction can be made as to the effect this will have on the comparative prices of the finished steels, it is obvious that the comparisons above are likely to be altered in a direction favorable to the molybdenum steels.

Some metallurgists are convinced that, at the same cost as competing steels, molybdenum steels produce a saving due to the way they handle in the shop on forging, heat-treating and machining.

An automobile producer compared two lots of steering knuckles, totaling 20,000, made respectively from 0.30 per cent. C, 1.25 per cent. Ni, 0.60 per cent. Cr, and from 0.30 per cent. C, 0.20 per cent. Mo, 0.60 per cent. Cr. Both steels were heat-treated to 270-320 Brinell. The number of pieces machined per grind of tool, averaging all the operations of drilling, reaming, tapping, turning, etc., was over twice as many on the chromium-molybdenum as on the chromium-nickel. A similar comparison made on axle shafts showed a 36 per cent. advantage for chromium-molybdenum. Still another comparison showed that chromium-molybdenum steel of 325 Brinell machined as well as 3½ per cent. nickel steel of 270 Brinell. On the two steels, heat-treated to the same tensile

[a] Chem. Met. Eng., Jan. 26, 1925.
[b] Iron Age, Jan. 29, 1925.

strength and Brinell hardness, the time of drilling, milling and reaming was found to be about half as great with chromium-molybdenum as with 3½ per cent. nickel.

Other tests do not show so great an advantage for molybdenum steels, but the weight of evidence indicates that the machining properties of these steels constitute a real advantage.

Pierce [275] has reported some data obtained in machining chromium-molybdenum automotive parts in competition with chromium-nickel parts of the same Brinell hardness, but the data are not convincing because no effort was made to determine the production per grind-of-tool on chromium nickel at speeds above "normal."

It seems generally admitted, also, that the heat-treating process requires less scrupulous control and may hence be cheaper than in the case of most competing steels.

At any rate it is evident that a large domestic supply of an element which will act in steel as the data cited above show molybdenum to behave, is an asset to the country.

As has been shown by excerpts and references, a good deal of well-agreeing data has been secured by various workers on the ordinary mechanical properties of molybdenum steels.

Molybdenum in Copper-Bearing Iron

While there does not appear to be any particular effect due to molybdenum in respect to the resistance to corrosion of steels into which molybdenum enters, the United Alloy Steel Corporation states [294] that after exhaustive experiments it is found that the addition of a small amount of molybdenum and of a larger amount of copper than is usual in copper-bearing iron or steel, to a low-carbon iron produces a combination superior in resistance to atmospheric corrosion, and suitable for culvert construction.

The particular combination, made under the Charls patents [187] which is advocated, is, 0.03 per cent. C, 0.12 per cent. Mn, 0.005 per cent. Si, 0.035 per cent. S, 0.005 per cent. P, 0.45 per cent. Cu and 0.07 per cent. Mo. This is termed "Toncan copper-iron-molybdenum alloy." This firm originally made sheets of commercially pure iron, later working into the production of copper-bearing iron of around 0.25 per cent. Cu, and from the results so far obtained, is inclined to think it likely that the 0.45 per cent. Cu, 0.07 per cent. molybdenum alloy will in turn become the largest tonnage sheet metal produced in its works. It is stated that molybdenum did not improve the pure iron or mild steel when no copper was added, that it did improve the iron carrying 0.20 per cent. or more copper, but had the greatest effect when the copper was raised to 0.40 per cent. or over. The

0.40 per cent. copper alloy without molybdenum is said to be decidedly inferior to that with molybdenum

The Cu-Mo iron is now being made in 100 ton lots in the open hearth furnace, the alloy additions being made in the furnace. The material rolls, galvanizes and fabricates like any pure iron or copper-bearing iron sheet.

Endurance Tests of Molybdenum Steels

Of true endurance tests on molybdenum steels, the only figures in the literature are due to McAdam,(118) who gave data in 1921 on a 0.41 per cent. C, 1.70 per cent. Ni, 0.12 per cent. Mo, and a 0.41 per cent. C, 1.00 per cent. Cr, 0.10 per cent. Mo steel. The results on these showed the same relation between tensile strength and endurance limit as was shown on chromium-vanadium or chromium-nickel steels.

In 1923 he gave data (47) on two steels of about 0.30 per cent. and 0.40 per cent. C, both with about 0.80 per cent. Cr and 0.20 per cent. Mo, and on one of about 0.50 per cent. C, 1.00 per cent. Cr, 0.20 per cent. Mo. Each steel was tested, after annealing at 1600° F. (870° C.) and also water-quenched from that temperature and drawn at 900° F. (480° C.) and 1100° F. (595° C.). These are compared with 3½ per cent. nickel steels of 0.30 per cent. and 0.40 per cent. C, with chromium-vanadium steel of 0.55 per cent. C, 1.00 per cent. Cr, 0.19 per cent. V and with chromium-nickel steel of 0.50 per cent. C, 1.75 per cent. Ni, 1.00 per cent. Cr comparably heat-treated, also with heat-treated carbon steels of 0.24 per cent. and 0.38 per cent. C. The ratios between endurance limit and tensile strength were as follows:

	Water-Quenched and Tempered	Annealed
.24 C.	.37–.46	.41
.38 C.	.40–.46	.42
.81 C.	......	.35
.97 C. .18 Ni	......	.37
.42 C. 3.60 Ni	.48–.59	.45
.31 C. 3.35 Ni	.45–.56	.48–.55
.39 C. .76 Cr .18 Mo	.50–.56	.45
.31 C. .85 Cr .20 Mo	.44–.45	.44
.50 C. 1.03 Cr .19 Mo	.49–.51	.45
.55 C. .99 Cr .19 V	.47–.56	.44
.49 C. .99 Cr 1.75 Ni	.50–.51	.43

That is, the chromium-molybdenum steel behaved on endurance tests, just like the other heat-treated alloy steels. In the annealed condition, the 0.30 per cent. C, 3½ per cent. Ni steel gave a slightly higher ratio than the chromium-molybdenum, chromium-vanadium or chromium-nickel steels, all of which acted alike.

Lewton (133) has compared a 0.91 per cent. carbon steel and four other spring steels of 0.46-0.49 per cent. C, 0.85-1.00 per cent. Mn, 0.88-1.22 per cent. Cr, two of which contained 0.16 per cent. vanadium

and one 0.18 per cent. molybdenum all quenched from 1600° F. (870° C.), the carbon steel drawn back to about 385 Brinell, the others to about 425 Brinell. Tests were made on bars of No. 1 gage, 2 inches wide, in the Upton-Lewis machine, the specimens not being reduced in dimension at the breaking section. Tests were run at stresses producing fracture in less than 300,000 cycles. A single test on the plain chromium steel was carried out at ten million cycles unbroken. Lewton states that no endurance limits were obtained, but that on the basis of the behavior at stresses above the endurance limits, the steels all showed practically the same fatigue characteristics.

While this conclusion is in agreement with other recent data on endurance of alloy steels, which show that at the same Brinell hardness different steels act alike on endurance test, the nominal stress at which the endurance limit might be expected to lie, from Lewton's tests above the endurance limit, is approximately 50,000 pounds per square inch or only about half the stress of the endurance limit which steels of this Brinell hardness show in tests on reduced section (hereafter called "necked") specimens. As will be brought out in the discussion of the Bureau of Mines experiments on un-necked specimens in the Upton-Lewis test, Appendix B, a test on un-necked specimens may fail to show real differences in endurance properties of different steels.

Notwithstanding that the few actual tests on endurance fail to indicate that molybdenum has any effect on endurance, the advocates of molybdenum, have made claims for exceptional endurance properties in molybdenum steel. Some of these claims, taken from advertisements,[134] are given below.

"You do not realize the terrific pounding that strains and wears your car. At last, tired by the constant rack of continual service, a part breaks. Vibration defied the genius of the builders of automobiles until the discovery and perfection of molybdenum steel reduced the destructive work of the road to a minimum. Molybdenum steel possesses greater resistant properties to wear, shock, strain and fatigue than any steel hitherto known. Every part of a car is made better and longer lived by the use of this American super-steel."

"Every buffet of the road strains, shocks, and wears your car. Jolts and jars that you do not feel because of springs and the upholstery weaken its resistance. Molybdenum steels make the light weight car strong enough, durable enough and tough enough to be fearless on the road. It resists wear and tear better than any other steel ever made. It makes stripping of gears almost impossible. It gives axles strength to resist the twisting strains of the road. It makes springs almost unbreakable. And to all parts it gives a durable toughness that prevents weakening from constant vibration."

Swinden's Arnold repeated impact tests [49] [50] on molybdenum steels of composition similar to those in present-day use, gave only about 100 to 200 alternations instead of 300, the figure given by Professor Arnold as satisfactory for steels to resist repeated stress.

Hoyt [15, p. 431] says that too little information is available concerning molybdenum steels,—the published tests, for example, dealing almost exclusively with tensile or static tests so that "the degree to which toughness is developed in molybdenum steels cannot be said to be generally known."

Data published since Hoyt made this comment, and cited above, indicate that molybdenum steels are equal to any others, on single blow, notched-bar impact tests, while Moore and Schaal,[111] as well as McAdam, find them superior on this score to comparable chromium-vanadium steels.

Cohade [135] found low ductility and woody fractures on transversely cut tensile test pieces on a 0.36 per cent. carbon, 0.47 per cent. molybdenum, 0.42 per cent. manganese steel, and on following this out on a couple of small laboratory test ingots, forged to a small square bar (30 x 30 mm.), which gave very tiny, transversely-cut test-pieces, he found a streaky structure and low ductility on the transversely-cut specimens from a molybdenum steel of 0.30 per cent. carbon, 0.12 per cent. manganese, 0.53 per cent. molybdenum; while on a plain 0.45 per cent. carbon, 0.47 per cent. manganese steel without molybdenum, the transverse specimens were ductile and not streaky.

From this he concludes that "it would therefore appear highly probable that molybdenum, even in small quantities, intervenes to accentuate the bad results of transverse tests."

However, Sargent [136] states that tests on molybdenum steel tested transversely to the direction of rolling gave no more evidence of transverse weakness than is shown by carbon steels.

Properties of Molybdenum Steels Requiring Further Study

The points which chiefly deserve study in order to establish more fully the effect of molybdenum in steel are, endurance properties, properties of notched specimens, and the properties of transverse specimens. Data obtained from experiments designed to fill these gaps will be given in Chapters 7 to 10.

Published Data on Cerium Steels

In contrast with the voluminous literature of molybdenum steel, data on cerium steel is conspicuous by its absence.

Moldenke [138] found that 0.10 per cent. "mix metal" (a mixture of metals of the cerium group) added to cast iron increased the transverse strength 10 to 25 per cent. and the deflection 18 to 33 per cent., giving a more fluid iron which fed the molds well, and froze more slowly, hence giving more graphitic carbon and a softer casting. No cerium was found to remain in the iron.

Spring [139] added 0.50 per cent. mix metal to cast iron and obtained 8 to 14 per cent. increase in tensile strength, 4 to 6 per cent. increase in transverse strength, 9 to 30 per cent. increase in deflection. The percentages of combined and graphitic carbon were unchanged as was the Brinell hardness. It was thought that the iron fed better.

Spring also tried mix metal in 0.35-0.40 per cent. C converter steel, adding 0.50 per cent. and 1.0 per cent. mix metal. The tensile tests on annealed specimens showed no improvement on two tests, and in these some specimens were low both in strength and ductility, due to "rusty colored inclusions," from which the metal did not free itself. On two other tests, ductility was increased, and the structure of the annealed steel was more uniform and less inclined toward ingotism. In all four heats, the sulfur content was reduced from an average of 0.085 per cent. to one of 0.037 per cent. The removal of manganese sulfide by action of the cerium is thought to account for the lack of ingotism and the increased ductility. With 0.50 per cent. cerium about 30 per cent. and with 1 per cent. cerium about 45 per cent. of the mix metal added was found in the steel.

Allison and Rock,[140] show micrographs of annealed converter steel treated with 0.10 per cent. and 0.15 per cent. mix metal which show very markedly dendritic structures. The mechanical tests show no change in the tensile strength or elastic limit, and ductility either unchanged or decreased. No reduction in sulfur content was found.

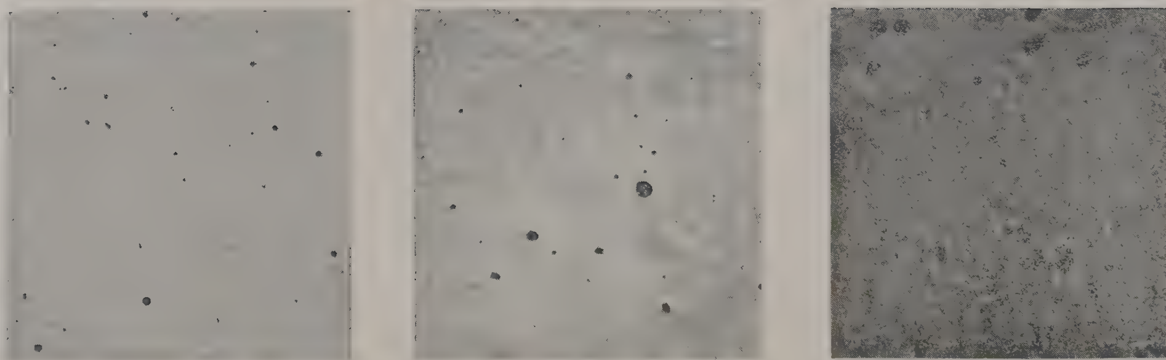
Tests were made with small amounts of cerium as a deoxidizer only in open hearth cast steel by a large steel foundry (tests reported but not made by the Fansteel Company) which, on annealed specimens, gave the following, each figure being an average from 4 to 8 specimens:

Heat	E. L.	T. S.	Elong.	R. A.	C	Si	Mn	P	S	Ce Added
AD45	40,500	70,000	31.0	53	.25	.27	.64	.028	.043	none
AD44	41,500	74,000	28.5	45	.27	.25	.58	.041	.042	.006
AD52	41,000	74,000	26.5	42	.29	.23	.52	.047	.042	.01
AD135	41,500	74,000	27.5	40	.29	.26	.59	.044	.045	.02
AD226	46,500	79,000	27.5	49	.33	.25	.60	.045	.037	.024
AD372	43,500	77,000	28.5	55	.25	.29	.70	.037	.037	.03
AD482	36,000	78,000	26.0	41	.28	.33	.53	.041	.046	.036

Heats AD135 and AD372 each gave one specimen of decidedly poor ductility. Micrographs of these steels were mostly not adapted for reproduction. The etched structures show no appreciable difference on the different heats.

The unetched (x 100) micrographs of Plate 1 show the general trend toward fewer but larger inclusions, as the amount added of cerium increases. There was no reduction in sulfur content.

The Crucible Steel Company made a few heats of cerium-treated steel which showed from 200,000 to 900,000 very tiny, globular, uniformly



All un-etched. × 100.

No cerium. | 2 oz. Cerium per ton. | 10 oz. Cerium per ton.

PLATE 1.—Inclusions in annealed. cerium-treated cast steel.

disseminated inclusions per square inch. No further details are available.

Tentative conclusions to be drawn from these scanty data and from the observations of the authors, are that even very small amounts of the cerium group of metals added to steel give rise to myriads of very tiny inclusions, probably oxide or sulfide. With increasing amounts of cerium and probably with increase in the time elapsing between adding the cerium and pouring the steel, these inclusions coalesce in greater or less degree. With sufficient cerium (0.50 per cent, or above) these inclusions may coalesce into large enough particles so that some of them rise to the surface, carrying out some of the sulfur, and under the most favorable conditions, reducing the amount of inclusions and thereby decreasing the tendency toward ingotism. If this cleansing action is incomplete or arrested too soon, the steel may be dirtier than the untreated steel and the physical tests are apt to be erratic, especially as to ductility. Small amounts appear to do more harm than good by introducing inclusions while the action of larger amounts is hard to control. In steel originally very high in sulfur, such as that studied by Spring, the net results may be good.

These tests deal only with annealed steel, not with heat-treated steels.

Burgess and Woodward [62] concluded from their tests of some of the cerium steels made by the authors that some cerium probably goes into solution and in some types of steel tends to produce a martensitic pattern in the air cooled steel. This would indicate some alloying tendency on the part of cerium.

The writers [63] have already recorded the details of the preparation of some 35 cerium steels. Desulfurization was usually, but not always accomplished.

The addition of 0.50 per cent. to 1.0 per cent. cerium metals to the steel just before pouring usually gave a reduction of 50 per cent. in the sulfur content, *e.g.,* 0.155 per cent. to 0.067 per cent. and 0.035 per cent. to 0.015 per cent. With less than 0.50 per cent. cerium metals added, desulfurization is very slight.

The word "cerium" is here used as a convenient shorthand for "mixmetal" or "metals of the cerium-group" *i.e.,* of a mixture of approximately the following composition:

Cerium	45 per cent.
Lanthanum	25 per cent.
Neodymium and Praseodymium	15 per cent.
Samarium	10 per cent.

While these metals are chemically very similar it is of course possible that the effects noted from the mixture may not be the same as those of

one of the pure metals, some one of which might be free from the faults of the mixture and have a good effect of its own.

Two heats of 0.30 per cent. carbon steels to which about 1 per cent. of cerium metals was added were made with the manganese held as low as possible. To one of these charges iron sulfide was added so that the manganese in the charge was insufficient to combine with the sulfur. Both steels showed a reduction of about 50 per cent. in sulfur content, and both forged well, though at least the one with added sulfur might have been expected to be red-short.

Evans [(286)] describes chromium-tungsten cutlery steels in which, he says, the sulfur must be kept low. He prefers to add silico-zirconium as a scavenger in the preparation of such steels, but mentions titanium and cerium as "equivalents of zirconium." Becket [(287)] comments on the "fixation" of sulfur by zirconium. It would appear that manganese, zirconium, titanium and cerium may all combine with sulfur so as to avoid or reduce the "red-shortness" of steel found when the sulfur is not so combined or fixed.

The cerium recovery, in the work of the writers, was in general low, only from 5 to 45 per cent. of that added being retained even when added just before pouring. If added at the beginning of the heat practically none was retained. When much cerium is found in the steel there was considerable segregation, such figures as 0.60 per cent. cerium in the top of a 70 pound ingot and 0.30 per cent. in the bottom being common. With 0.25 per cent. or less retained, segregation was slight.

Steels with above 0.15 per cent. cerium give out a decided acetylene-like odor on machining.

In most cases where 1 per cent. or more of cerium metals was added the ingots contained hair cracks only visible on a machined or polished surface. These appeared to be caused by the collection of some cerium-containing non-metallic material at the grain boundaries during freezing. In small 3 inch x 6 inch ingots of 75 to 100 pounds more than 0.30 per cent. to 0.40 per cent. cerium retained resulted in the formation of cracks, and for this reason it would appear difficult to utilize the desulfurizing action of cerium. On the other hand, in handling 75 or 100 pound lots of steel, the steel cannot be held molten in the ladle very long and the metal must be poured before enough time has elapsed to allow the non-metallic material to coalesce and rise to the surface. In lots of commercial size this separation may be much more complete, and with the elimination of the non-metallic material the tendency towards cracking should be reduced or eliminated.

There is an evident tendency in the cerium steels toward coalescence of the non-metallic material, [(63, p. 73)] but in no case, when working on the experimental scale was this anywhere near complete. The steels

contained myriads of non-metallic inclusions which under high magnification appear grayish, sometimes mottled with orange. They are probably some complex mixture in which cerium group oxides, or silicates, are present, and they probably carry some sulfur. The bottoms of the ingots usually contained less than the tops, and cracks were more prevalent in the tops than in the bottoms. The sulfur is probably combined with or adsorbed in the oxides or silicates as manganese or cerium sulfide. When this non-metallic material comes to the surface the sulfides oxidize and an odor of sulfur dioxide is evident. The sulfur dioxide odor was strong in all cases where such desulfurization took place.

The experimental ingots were either very dirty from these inclusions or cracked, with the cracks lined with material similar to that of the inclusions.

If cerium is to be used, it would appear necessary, in order to make clean and dependable steel, to secure the complete elimination of the inclusions, which is not an easy task in any steel,[(141)] and would be more than usually difficult with the cerium steels.

If cerium should change the type of inclusions to a less harmful form than that normally found in steel, or if it should improve the mechanical properties enough to more than compensate for the bad effect of the inclusions, it might be useful; but, in the absence of information of relative harm done by inclusions of different types, or of the influence of cerium on mechanical properties, the prospect for the use of cerium in steel is poor. Experimental data on the influence of cerium will be given in Chapters 7-10.

From a study of the literature which has been abstracted above it appears that a good deal is known about molybdenum and that its effect in steel is good. In fact the reported data are so good that many potential users have feared that they were too good to be true, or that there was some catch somewhere. One prominent steel maker has frankly stated that much of the "Mo-lyb-den-um" data has looked like propaganda, although based on good experimental facts.

It seemed desirable to have an impartial study of the alloying effect of molybdenum in steel with parallel tests of molybdenum and other alloy steels designed especially to supply missing data on endurance, impact and transverse static properties. When the experimental study of molybdenum steel was begun in 1920 data on these points were practically non-existent. Most of the important publications in this field have been made while the authors' work was in progress. The completion and publication of results of this work have been delayed because of the ambitious endurance testing program involved. The completion of this campaign has required 24 hour operation of two endurance testing machines over a period of three years.

The lack of data on the alloying power of cerium made it advisable to study that element also, and the two problems were carried on as a unit.

A few molybdenum and other alloy steels for comparison were obtained from commercial steel makers. But inasmuch as no cerium steels and relatively few different compositions of molybdenum steels were readily available from commercial sources, it was necessary to resort to laboratory manufacture of most of the steels to be used.

The general plan of work was to compare a series of steels of similar composition save for the alloying elements to be studied, utilizing a plain carbon steel or a vanadium steel for comparison, each steel being given different heat-treatments, usually three, the draw temperatures being chosen to cover the range from a very hard steel to a steel of moderate machineability. Special attention was paid to hard, strong steels of "spring temper," largely on account of the lack of endurance tests on such steels. With the large number of steels to be tested it was not possible to cover fully all variations in heat-treatment on which data might be desirable.

The idea in view of all the work was that of a general comparison of steels containing molybdenum or cerium with other steels of the same general class rather than a detailed study of any one particular steel.

Chapter 5.

The Effect of Molybdenum as Shown by the Transformation Points.

The phenomena of lowering and splitting of critical points on cooling with increase in cooling rate or with increase in maximum temperature to which austenite is heated, have been briefly discussed in Chapter 1, and the effect of some of the individual elements in making the austenite more sluggish and more ready to under-cool and show splitting has been mentioned in Chapter 2.

Many investigators [6, p. 358; 8, 142-145, 168, 246-255, 278, 288] have studied individual elements and have shown the inter-relation of rate of cooling, maximum temperature of heating and content of alloying element and of carbon.

A series of cooling curves taken with variation in any one of these four factors (the others being so chosen that the given variable shows up the split) has a family resemblance to a similar series in which one of the other factors is varied. The semi-air-hardening steels may readily be studied by changing the maximum temperature of heating, using the differential method of taking critical points and a rate of cooling easy to handle in the laboratory. Such a set of curves, from Jones,[110] is shown in Fig. 11.

Various investigators [31-35] have studied tungsten and chromium steels. In the higher alloy and carbon contents where special complications appear, due to carbides, the explanation of the experimental data may become very complicated, and most workers have their own theory for the exact mechanism of the changes taking place. When the method is carried to high-speed tool steels the matter is decidedly complicated, although such work makes it evident that the fundamental operation of hardening on quenching is the same whether in plain carbon steel, in quenched alloy steels, air-hardening alloy steel, or in high-speed tool steel.

Whatever the exact mechanism may be, it is obvious that, the alloying element, whether in elementary form or as some compound with carbon or with iron must be taken into solution in austenite and this solution allowed to diffuse so as to become homogeneous for the maximum retarding effect of a given percentage of the alloying element to be shown on the cooling curves.

Swinden [49, 50] [53, 54] studied the critical points of tungsten and molyb-

denum steels in detail and French [55] has recently determined critical point curves for two steels containing molybdenum. Swinden used different maximum temperatures and the same cooling rate, while French varied both.

Both observers found, for each steel, for a given rate of cooling, a certain temperature to which the austenite must be heated to produce the split transformation. Swinden ascribes this phenomenon to some change in state of the molybdenum, or of some iron-molybdenum compound, while French ascribes it to some obscure molybdenum change.

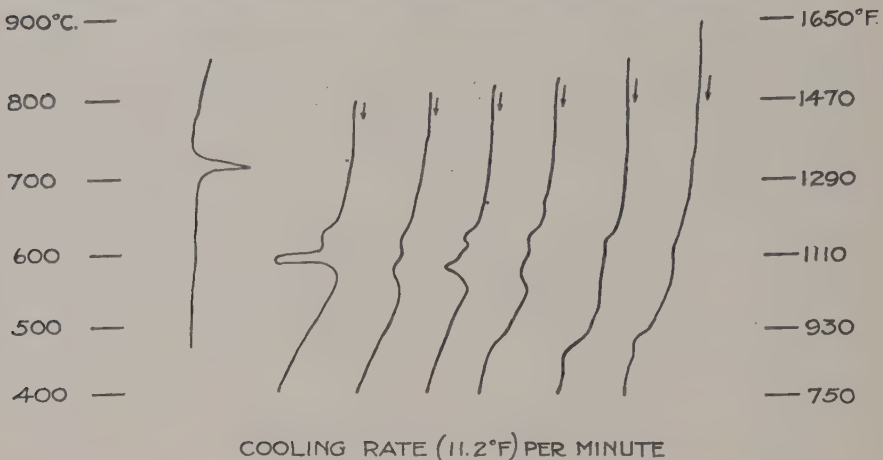


FIG. 11.—Effect on critical points of varying maximum temperature in a semi-air-hardening steel, from Jones.

Sargent [95] states that the lowering and splitting of the critical points on cooling is shown by steels containing only 0.20 per cent. to 0.50 per cent. molybdenum, but gives no cooling curves.

To show the relative stabilizing power of molybdenum in the various steels to be tested, critical point curves were taken both on heating and on cooling.

The differential method was used, the specimens weighing approximately 50 grams, and a 50 gram neutral body of nickel was employed. The temperature difference between specimens and neutral body was indicated by a platinum-platinrhodium-platinum differential thermo-couple used with a galvanometer capable of being read to 0.002 milli-volts. The temperatures of the specimens were read by a platinum-platinrhodium couple and a Leeds and Northrup portable potentiometer. This could be read to about 2° C. The specimen and neutral body were heated in a small wire-wound electric furnace and the rate of heating and cooling was manually controlled by a 30 step rheostat.

The rate of heating and cooling can be found from the curves of

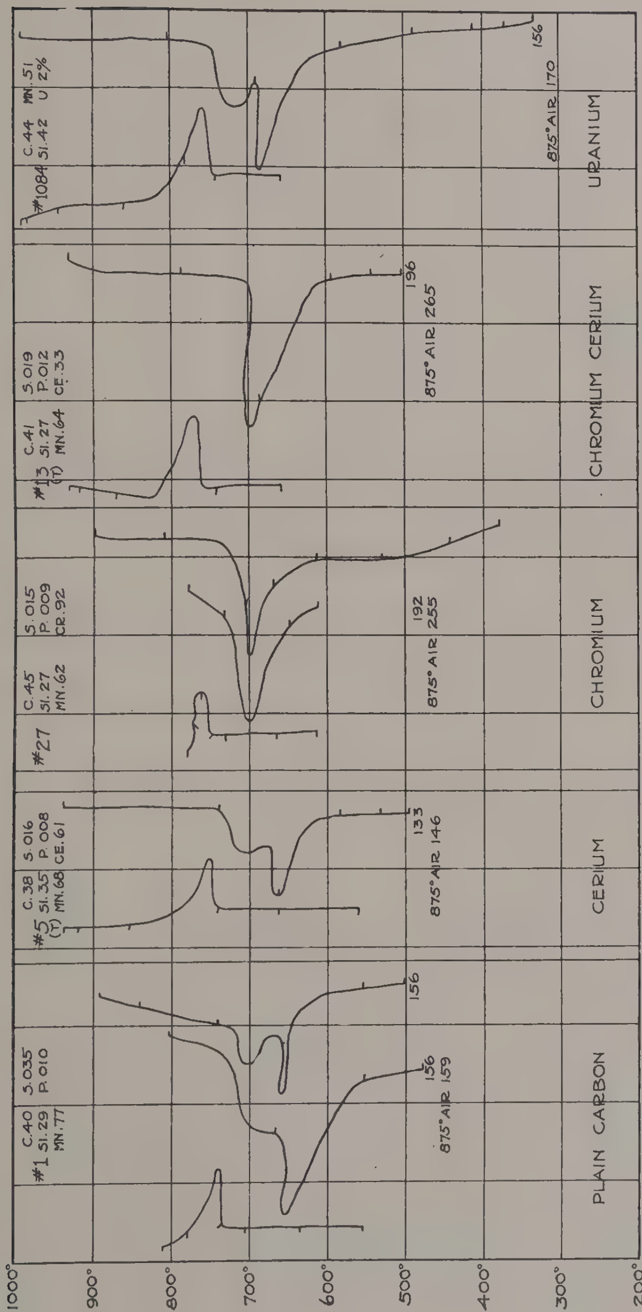


FIG. 12.—Critical point curves of carbon, cerium, chromium and uranium steels.
(Steel No. 13 contains 0.98 per cent. chromium besides the elements shown in the caption.)

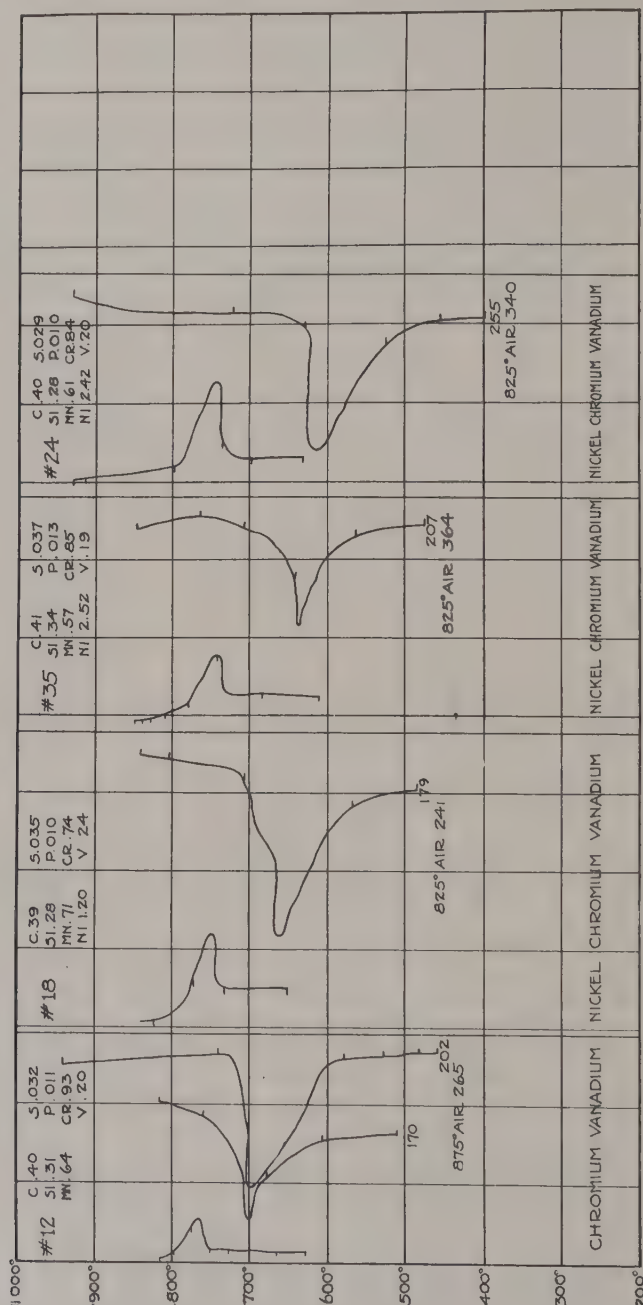


FIG. 13.—Critical point curves of Cr-V and Ni-Cr-V steels.

Figs. 12-21. A short horizontal mark is made on each curve at the temperature of the specimen at each 15 minute interval. The rate of cooling was usually 3 to 5 degrees C. per minute, while the heating rate was still lower.

Fig. 22 gives unpublished curves for three chromium-molybdenum steels, supplied by Mr. J. D. Cutter of the Climax Molybdenum Company and a curve for one nickel-chromium-molybdenum steel taken from Jones.[110]

In the authors' curves, Figs. 12-21, beneath each cooling curve is given the Brinell hardness number of the steel after cooling completely in the critical point furnace. There are also given, for comparison, the temperature from which the 50 gram specimens were cooled in air and the Brinell hardness number after that treatment.

In the plots, steels of comparable compositions have been grouped together. Most of the steels contain about 0.40 per cent. carbon and 0.70 per cent. manganese.

Steel No. 1, plain carbon, Fig. 12, gives the same critical points whether cooled from 800° C. (1470° F.) or 890° C. (1630° F.). Steel No. 5 with 0.60 per cent. cerium shows no appreciable difference from the plain carbon steel, save in a slight increase in Ac_1

Chromium steel No. 27 shows that this composition gives the same critical point whether cooled from 775° C. (1425° F.) or 895° C. (1640° F.); with this carbon content (0.45 per cent.) Ar_{3-2} merging with Ar_1.

The chromium-cerium steel No. 13 gives curves very much like No. 27. An uranium steel No. 1084, with 0.44 per cent. C, 2 per cent. U, shows no lowering, nor splitting, although cooled from 990° C. (1815° F.). The steel is not air-hardening. Poluskin [61] found that uranium had no appreciable effect on the critical points. The chromium-vanadium steel No. 12, Fig. 13, acts like the plain chromium steel No. 27.

Comparing the plain 1.25 per cent. Ni, 0.75 per cent. Cr steel No. 15, Fig. 14, with similar steels No. 18, Fig. 13, containing vanadium, and Nos. 20 and 52, Fig. 14, containing cerium, it is noted that neither vanadium nor cerium has any marked effect.

In the class of steels with 2.5 per cent. Ni, 0.90 per cent. Cr, No. 21, Fig. 15, without vanadium or cerium may be compared with Nos. 24 and 35, Fig. 13, containing vanadium and Nos. 25 and 36, Fig. 15, containing cerium.

In these there is noted the lowering of the critical points Ar_{3-2-1} without the splitting which is normal to steels of this composition, and the lowering depends on the maximum temperature used. However, there is no marked effect to be definitely ascribed to vanadium or cerium. Again, in steels I-9 and I-32, nickel-silicon steels with and without cerium, Fig.

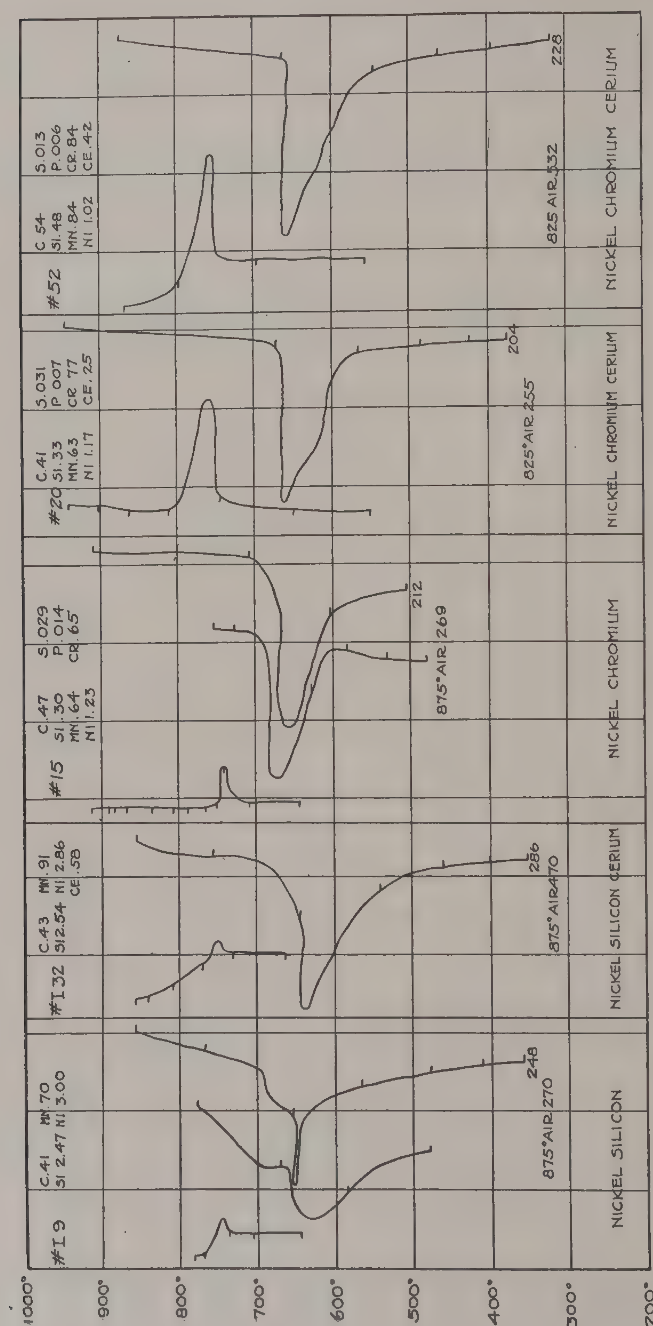


FIG. 14.—Critical point curves of Ni-Si, Ni-Si-Ce, Ni-Cr, and Ni-Cr-Ce steels.

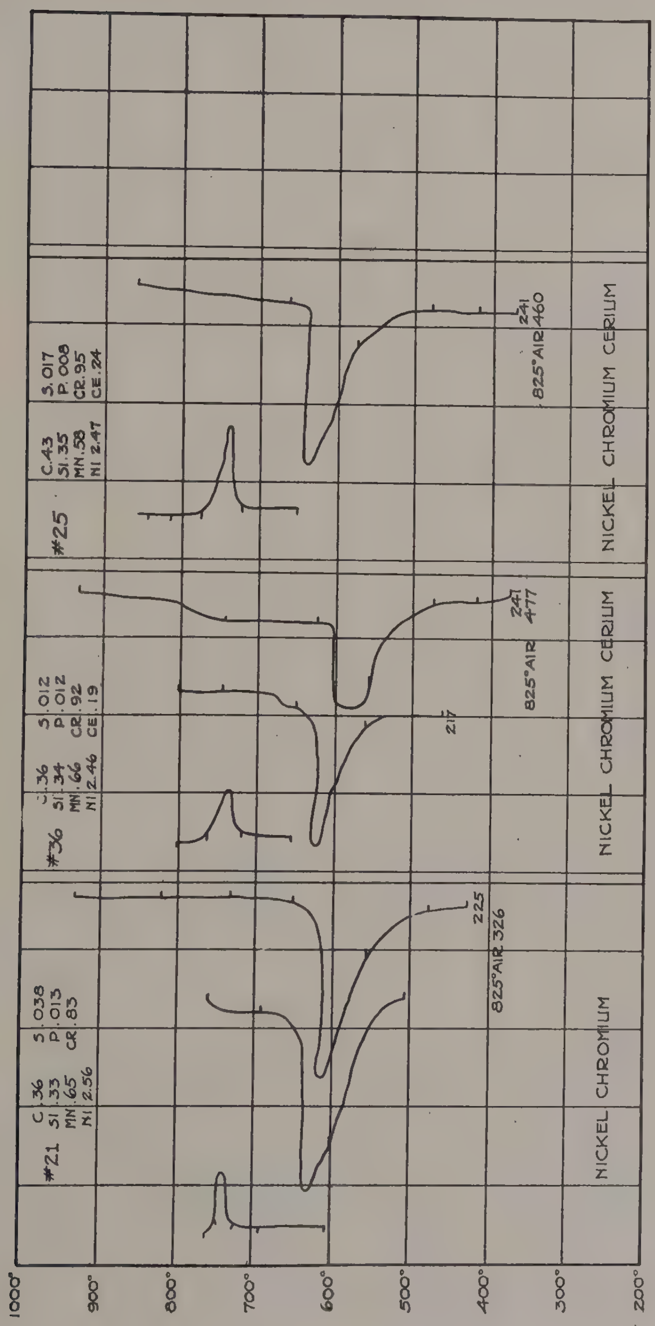


FIG. 15.—Critical point curves of Ni-Cr and Ni-Cr-Ce steels.

14, the cerium does not greatly affect the shape of the cooling curve. Steels Nos. 35, Fig. 13, 24, and I-32 show greater air-hardening power than No. 21 or I-9, probably due more to differences in carbon, chromium and manganese content, than to the presence of vanadium or cerium. Steel No. 52, Fig. 14, a chromium-nickel steel with cerium air-hardens almost completely, but it would be air-hardening without the cerium. On the whole, it appears that cerium may slightly increase the propensity for hardening, but not sufficiently to show up on cooling curves at the cooling rate here employed, and that vanadium, when present in the usual small quantities, has no notable effect on the cooling curves or on the propensity for hardening.

In sharp contrast to the lack of effect of cerium and vanadium, is the marked effect of molybdenum.

In the carbon-molybdenum steels Nos. 3, 2, 41, 39, 43, Fig. 16, 42, 44 and 40, Fig. 17, cooling from 800° C. (1470° F.) gives curves indistinguishable from those of a similar carbon steel without molybdenum, but cooling from about 860° C. (1615° F.) invariably alters the curve. In the case of No. 3, with only 0.37 per cent. molybdenum and with carbon slightly on the low side of the average for this series, Ar_1 is lowered, but not split. Raising the temperature to 980° C. (1800° F.) has no further effect over that shown from 880° C. (1615° F.).

In No. 2, with 0.67 per cent. molybdenum, however, and in the steels of higher molybdenum content, cooling from 880° C. (1615° F.) or above, results in the appearance of Ar'', starting around 550° C. (1020° F.) and with a maximum around 500°-450° C. (930°-840° F.). Raising the temperature does not greatly affect the results, Ar'' dropping but slightly in temperature and not increasing greatly in intensity, and the upper point not being obliterated except in No. 40, of high carbon content. Only in No. 40 is any marked tendency toward air-hardening shown. It is seen that 0.67 per cent. molybdenum has practically the same effect as 2 per cent. or 3 per cent. molybdenum, though the obstructing effect on the austenite tends to be obtained at slightly lower temperatures, with molybdenum high.

In these plain molybdenum steels Ar'' occurs at temperatures well above the range at which martensite is stable, so that the martensite formed in cooling through Ar'' is not preserved without quenching.

The propensity toward hardening, on quenching, is, however, very obviously greater than in the absence of molybdenum.

Swinden [53] [54] found that after cooling from temperatures which gave a very strong Ar'', the Ac_1 was higher on the next heating, and that repeated heating just past Ac_1 was required to place Ac_1 at its original value. No such effect was noted in this work, Ac_1 being constant whether Ar'' had or had not appeared on previous cooling.

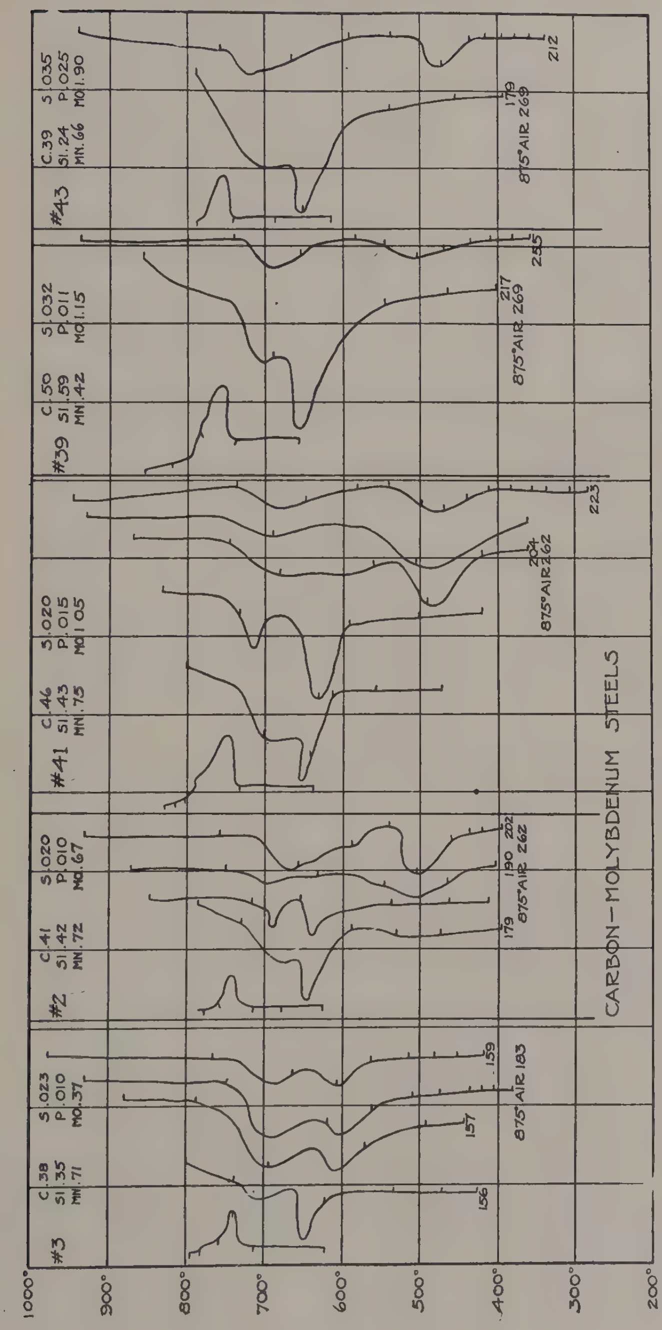


FIG. 16.—Critical point curves of C-Mo steels.

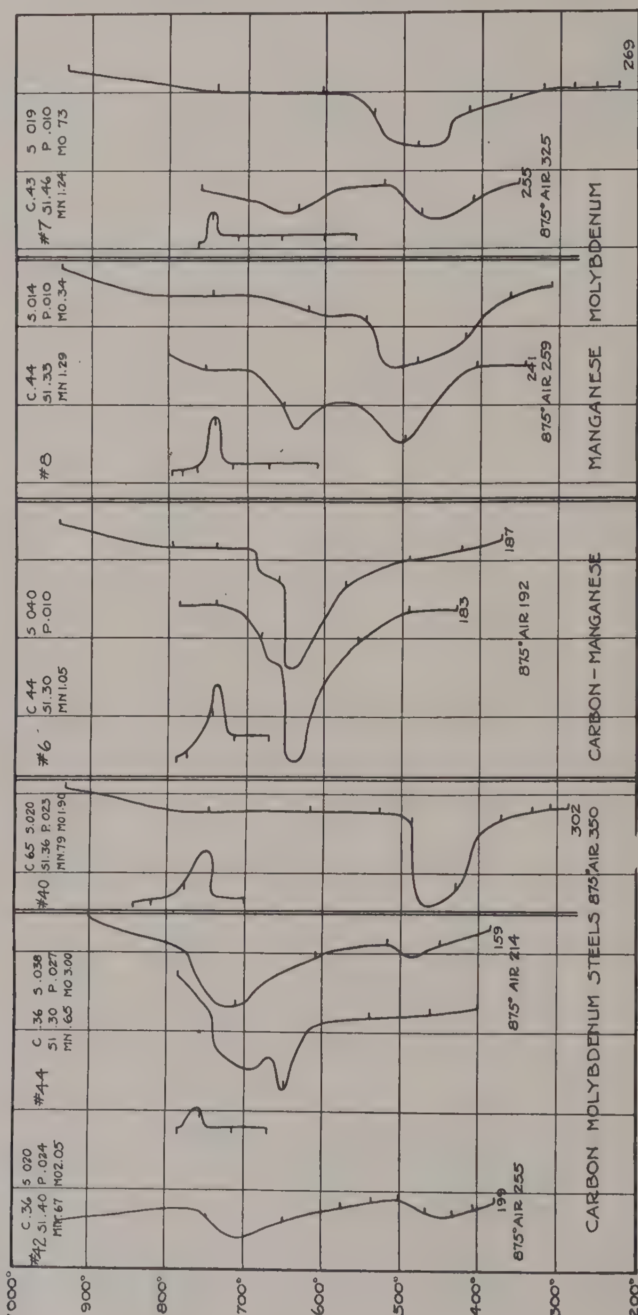


FIG. 17.—Critical point curves of C-Mo and Mn-Mo steels.

On cooling from, 960° C. (1760° F.) or above, French [55] found that a 0.20 per cent. C, 0.41 per cent. Mn, 0.94 per cent. Mo steel gave an additional critical point at about 860° C. (1580° F.), shown on an inverse rate curve, although no difference was found in the mechanical properties of the steel whether quenched from 910° C. (1670° F.) or from 980° C. (1800° F.) and subsequently tempered in both cases. Swinden did not find this extra critical point in a steel of similar composition. French did not find this 860° C. (1580° F.) point in a steel of 0.27 per cent. C, 1.01 per cent. Mn, 0.88 per cent. Cr, and 0.52 per cent. Mo.

The only carbon-molybdenum steel heated to above 950° C. (1760° F.) in the authors' experiments was No. 3, with more carbon and manganese and less molybdenum than the steel used by French. No such extra point was noted in cooling this steel.

That the effect of molybdenum in splitting and lowering the critical points is enhanced in the presence of other elements which have the same tendency, is shown by steels Nos. 6, 7 and 8, Fig. 17, in which manganese has been increased to 1 to 1.25 per cent. Without molybdenum, raising the maximum temperature from 790° C. (1450° F.) to 940° C. (1725° F.) has no effect. With the addition of even 0.34 per cent. molybdenum, Ar″ appears even when the steel is cooled only from 800° C. (1470° F.) and Ar′ disappears when it is cooled from 940° C. (1725° F.).

The chromium-molybdenum steels of low carbon and low molybdenum content, Nos. 47, 46, Fig. 18, show only slight indications of lowering of Ar_1 and no splitting, *i.e.*, no Ar″. The same is probably true of No. C-153, Fig. 22, from the Climax Molybdenum Company's data, although the cooling was not carried to a sufficiently low temperature to determine this with certainty.

No. 45, Fig. 18, 0.40 per cent. C, 0.65 per cent. Mn, 0.88 per cent. Cr, 0.30 per cent. Mo, shows only a slight splitting on cooling from 950° C. (1740° F.), while No. 29, 0.38 per cent. C, 0.65 per cent. Mn, 0.84 per cent. Cr, 0.35 per cent. Mo shows it strongly from 875° C. (1600° F.). Slight differences in cooling rate may affect the curves, but the air-hardening tests also show No. 29, Fig. 19, to be more susceptible to hardening than No. 45. The extra .05 per cent. molybdenum apparently throws No. 29 over the line for the cooling rate used.

No. 48, Fig. 18, with lower chromium and still higher molybdenum, as well as No. C-144, Fig. 22 (from the Climax Molybdenum Company's data) are strongly split when cooling from 900° C. (1650° F.) No. 29, Fig. 19, is strongly split from 875° C. (1600° F.), while No. 11, of almost the same composition, has Ar_1 lowered, but not split, on cooling from 915° or 935° C. (1675°-1715° F.).

The Ar points are strongly split in cooling the higher carbon steel No. 51, Fig. 19, (0.53 per cent. C, 1.09 per cent. Cr, 0.44 per cent. Mo)

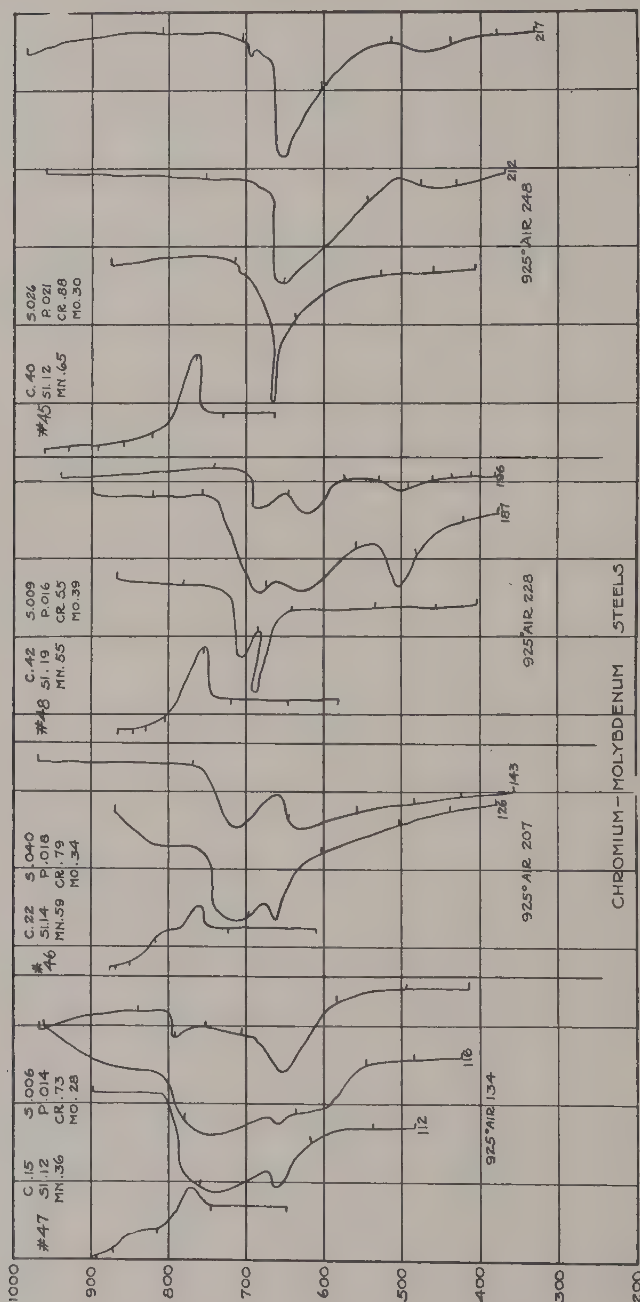


FIG. 18.—Critical point curves of Cr-Mo steels.

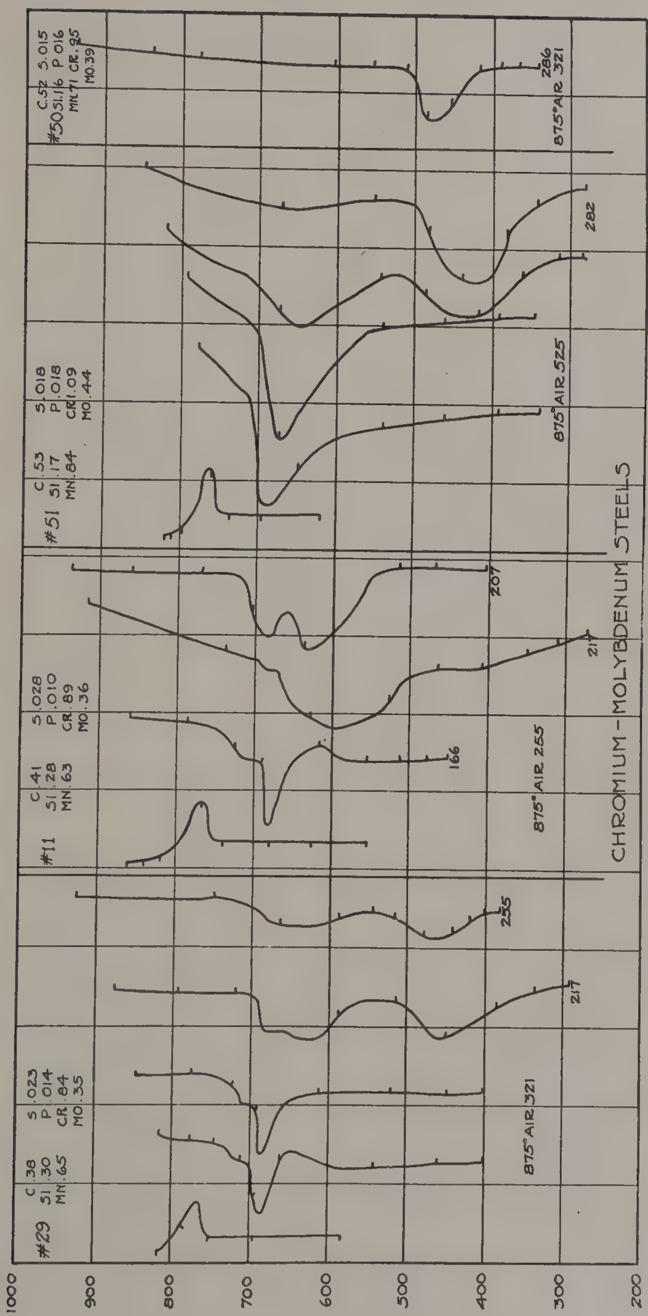


FIG. 19.—Critical point curves of Cr-Mo steels.

from 820° C. (1510° F.) and Ar′ is almost obliterated in cooling from 850° C. (1560° F.). This steel is strongly air-hardening, giving 525 Brinell hardness when air-cooled from 875° C. (1600° F.). No. 50 with .05 per cent. less molybdenum shows Ar′ entirely wiped out from 930° C. (1700° F.), but it is only slightly air-hardening from 875° C. (1600° F.), giving 321 Brinell hardness.

Although the low-carbon low-molybdenum steels did not show the split transformation readily, No. 49, Fig. 20, of 0.25 per cent. C, 0.48 per cent. Mn, 0.95 per cent. Cr, 0.75 per cent. Mo, gives a very strong Ar″ from 830° C. (1525° F.). In No. 10, and No. 28 of around 0.40 per cent. C and 0.70 per cent. Mo, splitting appears at 800° C. (1470° F.).

When we come to the 1.75 per cent Ni, 0.75 per cent Cr. steels, No. 15 without molybdenum, showed a slight lowering of Ar_1, but no splitting. The addition of 0.31 per cent. molybdenum, as in No. 17, Fig. 20, causes strong splitting, even from 770° C. (1420° F.), and the addition of 0.83 per cent. molybdenum, as in No. 16, wipes out the upper point almost completely and gives practically only Ar″, from 785° C. (1445° F.).

In the 2.5 per cent. Ni, 0.80 per cent. Cr series cooling from 760° C. (1400° F.) even when only 0.35 per cent. molybdenum is present, gives only a trace of Ar′ and shows Ar″ developed almost to its fullest extent, as in Nos. 34, 23 and 37, Fig. 21. In a similar steel of 0.25 per cent. C, 2.84 per cent. Ni, 0.85 per cent. Cr, 0.48 per cent. Mo, Jones,[110] Fig. 22, shows the same thing. These curves may be compared with Jones' curves Fig. 11 for a similar steel without molybdenum. With still higher molybdenum as in Nos. 33, 22 and 26, Fig. 21, complete elimination of Ar′ is shown on cooling from any temperature above the completion of Ac_3. These nickel-chromium-molybdenum steels of about 2.5 per cent. Ni, 0.80 per cent. Cr and 0.40 per cent. or more Mo are strongly air-hardening, giving 512-600 Brinell hardness on air-cooling from 825° C. (1515° F.).

Jones, however, found that a steel of 0.28 per cent. C, 2.45 per cent. Ni, 0.65 per cent. Cr, 0.45 per cent. Mo, in 1 inch x ½ inch x ½ inch section, air-cooled from 900° C. (1650° F.) or 1200° C. (2190° F.) gave 317-325 Brinell hardness. Since a Brinell hardness of 302 to 390 was developed by furnace cooling of the 0.38 per cent.-0.53 per cent. C steels of the nickel-chromium-molybdenum group it seemed possible that specimens larger than the 50 gram specimen used in the air-hardening test might not harden completely on air-cooling, so oil-quenching was used in the heat-treatment to insure complete hardening, even though such steels as Nos. 26 and 37 appeared to be fully air-hardening in a 50 gram mass.

Although the 2.5 per cent. Ni, 0.80 per cent. Cr steels, with molybdenum, show Ar″ from 760° C. (1400° F.), steel No. I-30, Fig. 21, with 2.75 per cent. Ni, 2.50 per cent. Si, 0.70 per cent. Mo, but no chromium,

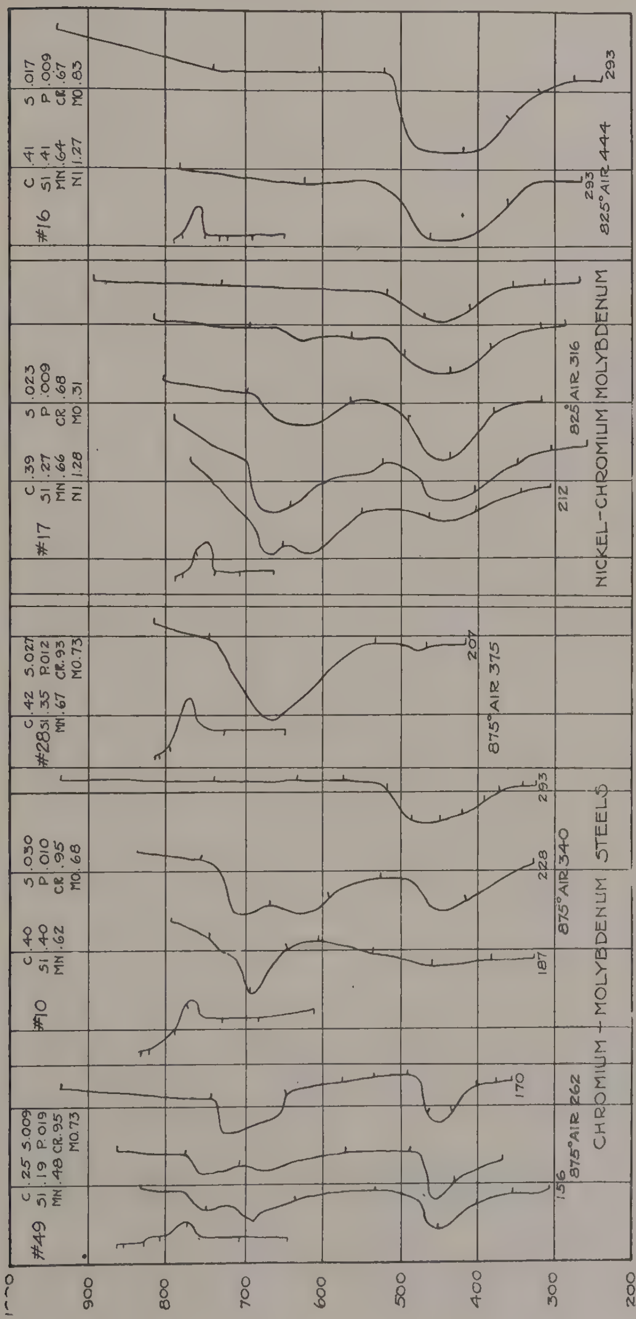


FIG. 20.—Critical point curves of Cr-Mo and Ni-Cr-Mo steels.

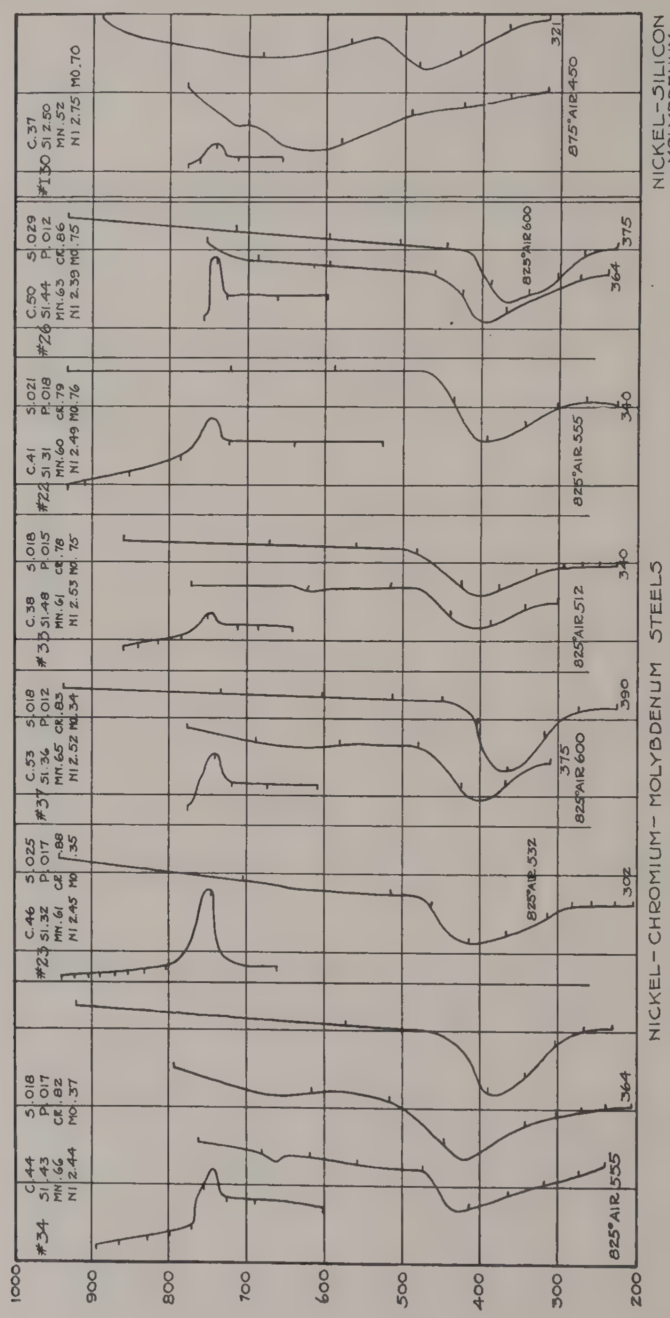


FIG. 21.—Critical point curves of Ni-Cr-Mo and Ni-Si-Mo steels.

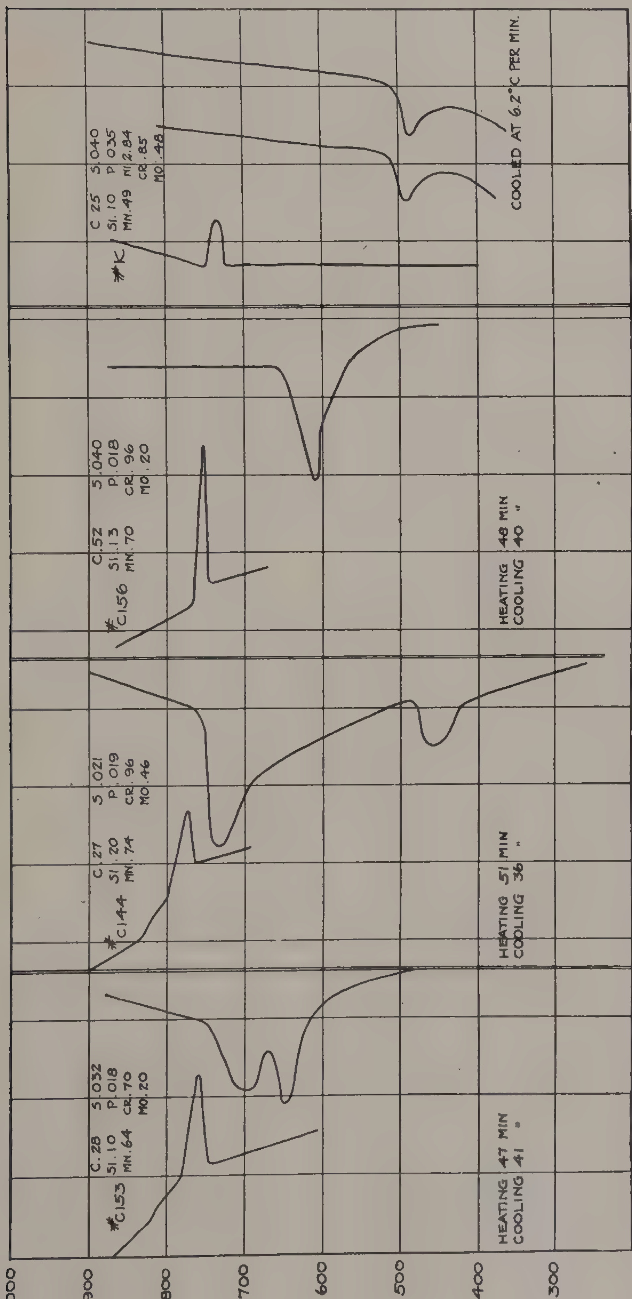


FIG. 22.—Critical point curves of Cr-Mo and Ni-Cr-Mo steels. Cr-Mo from Climax Molybdenum Co. data, Ni-Cr-Mo from Jones.

did not show Ar″ from 780° C. (1435° F.). However, when cooled from 890° C. (1635° F.) Ar″ was strong and Ar′ practically absent. The chromium plays an important part in the splitting of the transformation points of chrome-nickel steels.

The effect of molybdenum in lowering and splitting the points is evident in carbon steels, but is more readily shown in conjunction with nickel, manganese, chromium, or a combination of these elements. The higher the carbon content is, the more readily the splitting and lowering occurs. Griffiths [288] has noted the mutual effect of carbon, nickel and chromium.

Molybdenum is one of the most active of these elements in this regard, and Swinden [49, 50, 53, 54] has shown it to be more active than tungsten.

The curves given tell only part of the story, because the cooling rates have not been varied. Were the cooling rates increased, the effect of molybdenum would doubtless be evident in the lower carbon, lower molybdenum steels in which it does not appear to have much effect at the slow cooling rates used.

The evidence of the curves, however, unmistakably shows that molybdenum exerts a most profound effect on the propensity for hardening. This offers an adequate explanation for the depth-hardening properties of steels containing molybdenum. It is also clear that the large thermal hysteresis of these steels gives considerable lee-way in the quenching operation, since the steels can be cooled to just above the upper critical point on cooling before quenching and still get maximum hardness.[146] When quenching in spring-forming machines this is a decided advantage.

From the evidence of the cooling curves, cerium is not of value in increasing the propensity to harden, and does not fall into the group of active alloying elements. Any effect that it may have would then be expected to be specific.

Chapter 6.

Importance of Dynamic Tests.

A fairly complete testing program will involve the making of complete tensile tests; hardness tests, such as the Brinell, Shore or Rockwell; repeated-blow tests, like the Stanton; notched-bar impact tests, like the Izod or Charpy; and endurance tests of some kind, such as the Upton-Lewis reversed-bending or the Sondericker (Farmer) rotary-bending test.

In interpreting data secured in a testing program of this kind, the question arises as to just what each test shows regarding the quality of heat-treated steel.

Tied up in the complete tensile test are the most important facts the engineer needs in consideration of materials for application under static load.[147] The proportional limit tells what stress may be imposed if no permanent change of dimensions is allowable. The yield point shows the limit of usefulness for cases where a slight change of dimensions is immaterial. The tensile strength tells what stress the structure will stand before failure, as well as something about the machineability. The elongation and reduction of area indicate whether the material is brittle or tough. With some little knowledge of the composition of the steel in hand, its history and heat-treatment, the results of the tensile test will make possible a fair guess as to the strength in compression, in shear and in torsion. This is true because of the inter-relations between the mechanical properties, which are shown graphically in Fig. 1, p. 19.

The tensile strength indicates roughly the degree of ductility to be expected, ductility rising as the strength falls. Differences in ductility, (best measured through reduction of area, at the same tensile strength or proportional limit), then serve to differentiate two steels. In general, at the same tensile strength, the steel with the higher ductility is the better because it requires more energy for fracture as a result of yielding for a longer period before breaking.

Attempts to approximate the energy of rupture from the product of tensile strength and elongation, or by other calculations such as the "merit index" [148] are useful in getting an approximation of the energy-absorbing power of the steel. They serve, within limits, to compare two steels, but are not truly accurate. The area of the stress-strain diagram up to the maximum load would be a better criterion, but this data is

seldom available, because, in testing, the ordinary extensometer should be removed before this portion of the curve is reached.

Moreover, the toughness deduced from the tensile test may be entirely misleading as to the ability of the steel to withstand sudden shock, especially in the "notched" condition.

Tensile testing, aside from lack of agreement as to what should be measured as an "elastic limit", is quite well standardized and the results have a definite meaning.

The dynamic test, *i.e.*, single-blow and repeated-blow impact tests and endurance tests, are less well standardized either as to methods of testing or interpretation of results.

There is much discussion among testing engineers as to whether or not the single-blow notched-bar impact test tells anything about the service value of the steel.

There are a score of impact machines and a variety of sizes and shapes of specimens and notches for each. Results from one machine or one test-piece are not quantitatively comparable or convertible to, results on other machines or test-pieces. Because of lack of standardization, intercomparison of impact results is difficult, and generally only of qualitative value.

It is therefore essential that the same machine and same test-piece be used throughout the study of any series of steels. The Charpy and the Izod tests are the most nearly standard. Either one, used on a series of steels will usually place the steels in the same order.

The single-blow notched-bar impact test shows up brittleness in a steel, whether that brittleness be due to high phosphorus, high carbon, or to unrelieved quenching stresses. Shock tests will also show the increased brittleness of steel with decreasing temperature.

The work done in an impact test may be low either because the material is lacking in ductility or in strength, as both are factors in the work required for rupture.

The change in Izod values with draw temperature for one carbon steel are shown by Fig. 23 to bear a close relation to the ductility, up to the annealing temperature. Above annealing temperature (as shown by the plot of the nickel-chromium steels), the Izod values fall. On some alloy steels, there are two maxima in the plot of Izod figures vs. draw temperature and this appears to be the general type of curve, although in carbon steels the lower maximum is not marked.

In Fig. 1, page 19, are shown the results of three different single-blow impact tests, the Izod, Charpy and Fremont. The curves for the three tests are quite similar and are of the same type as the curves for "degrees of twist" in torsion testing or "reduction of area" in the tension test.

Single-blow shock tests on longitudinal and transverse specimens of

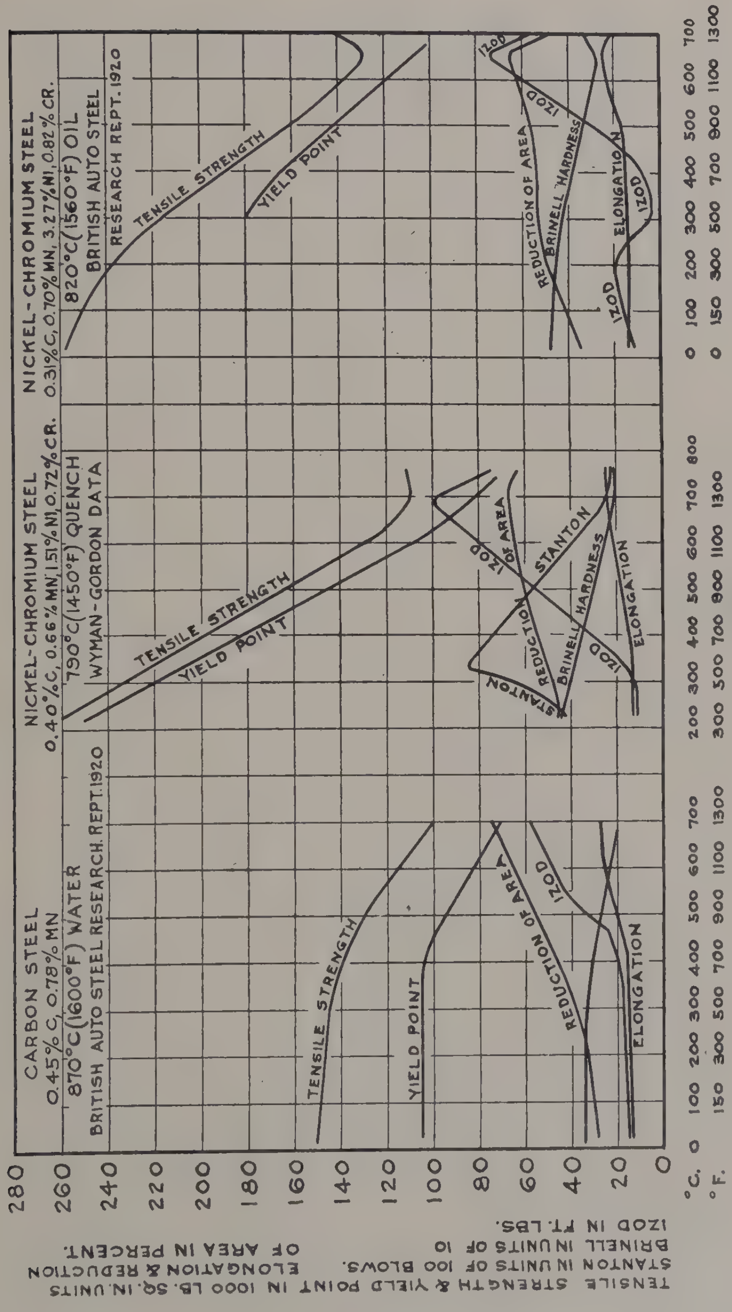


FIG. 23.—Relation of Izod test figures to other mechanical properties of heat-treated steels.

wrought material give much lower figures on the transverse pieces when inclusions are present. Brearley [149] advocates the impact test for showing dangerously dirty steel in cylinders for compressed gases. The transverse impact figure should, he says, be not less than half the longitudinal figure.

Aitchison [150] advocates a high ratio of transverse to longitudinal notched-bar impact values for die block steel.

Petrenko, in work at the Bureau of Standards, soon to be published, shows that beside the well-known difference in longitudinal and transverse impact tests due to non-metallic inclusions or to inhomogenetics of structure there is, in such dirty or inhomogeneous materials, a difference in impact figures for longitudinal test, specimens taken from flat rolled bars, according to whether the notch is cut on the top or side of the specimen. Such tests throw much light on the directional properties of the material.

Single-blow notched-bar tests on some heat-treated alloy steels show differences [151] depending on whether the steel is slowly cooled after the draw or rapidly cooled, as by quenching; the latter method giving the higher impact values. No other test shows up this temper-brittleness or *"Kruppkrankheit."*

Abbott, [152] however, believes that service records on airplane crank shafts show more failures in service from pieces that had given a high shock test than those that had given a low one. On the other hand, the Bureau of Standards [153] examined a broken crank-shaft from a small Liberty engine, and found no mechanical properties lower than the normal with the exception of the Izod figure, which was below the average for the composition and heat-treatment of the steel.

The effect of varying the quenching temperature of a chromium-vanadium steel, the draw temperature being held constant, is shown by Stagg, [154] who finds that from just above Ac_3 to a quenching temperature of 925° C. (1700° F.) the impact figures rise, but as the quenching temperature is raised still farther the impact figures fall.

Mathews [155] finds that the Izod test gives lower values for coarser grained material.

Langenberg [156-158] and Thomas [158a] find the impact test of very great value in obtaining satisfactory ordnance material, and are thoroughly convinced of the practical value of the test. The critical impact value for a specific service must be determined by a careful study of failed and satisfactory material. Jones, [110] of the Woolwich Arsenal, reports on many Izod tests for temper-brittleness, and the impact test appears to be valued highly at Woolwich. Rolfe [300] states that material for eyebolts, unsuitable through brittleness, was not detected by tensile test but was detected with certainty by the Izod test. Hoyt [159, 160] is a strong

advocate of the notched-bar test and cites several cases where it has served to show the cause for failure in service.

Burgess [62, p. 143] says, "a high impact value does not always indicate a superior steel since such values are many times accompanied by low tensile strength. . . . Those steels that show fair values of impact together with high tensile strength should be considered the best steels, since they combine strength with toughness."

Dix, [161] after a comprehensive study of single-blow tests for the Bureau of Aircraft Production, concluded that "the notched-bar impact test is satisfactory and necessary as a plant control proposition." Jenkin [162] believes that the single-blow notched Izod test does not indicate the resistance of material to impact or shock, and should not be called an impact test; that it is mainly valuable as indicating whether the heat-treatment has been properly carried out; that the results indicate differences of condition that cannot be demonstrated in any other way; and that while no conclusive experimental evidence has been obtained to prove that a condition of steel giving a high notched-bar test is any better than that of the same steel giving a low test, yet experience with broken engine parts indicates that high-test steel is the better.

He emphasizes the fact that the Izod value cannot be considered apart from the other properties of the steel; what is a high Izod test for a hard steel is a low one for a soft steel; also that slight differences in Izod figures are without significance. He says: "Izod values are really one of two things—good or bad." If they are reasonably near the value found by experience as standard for a given steel in a given condition, the steel is to be regarded as satisfactory, while values far below indicate a bad steel.

Aitchison [10, pp. 125, 138, 196] takes practically the same attitude as Jenkin. He gives a curve showing the Izod values to be expected in properly heat-treated alloy steels of varying tensile strengths. He states that three properties—the proof load, the fatigue range, and the notched-bar value "appear to be the real criteria which the engineer should apply to his steel."

While the figures obtained on a single-blow notched-bar test cannot be directly used in engineering design, the qualitative information given by such a test, in connection with other tests, serves more clearly to define the properties and probable usefulness of the steel.

Repeated Impact Tests

Still less is known about the relation between repeated impact tests on notched test specimens and the service value of the material tested, than in the case of the single-blow test.

Repeated impact machines such as the Eden-Foster, Amsler, Matsumara, [289] Krupp, [163] and Stanton machines are used relatively little.

Rittenhausen and Fischer (164) discuss the effect of various factors such as the shape of notch and method of testing on the Krupp machine, and state that steam hammer parts which formerly failed promptly from repeated shock have been made to last indefinitely by using special alloy steels whose composition and heat-treatment were worked out by means of tests on the Krupp machine.

Fig. 1, p. 19, shows that the result of the Stanton test is not a function of any one of the commonly-measured properties of steel. Starting with very hard steels the Stanton figure increases with decreasing Brinell hardness to a maximum, and then falls again. Hence the same steel can show identical Stanton results at two widely varying hardnesses. The curve of Fig. 1 is for only one height of fall of the hammer, *i.e.*, one strength of blow for all steels, and its shape and the location of its maximum might change were the comparison made on the basis of other heights of fall.

On account of the notch the force of the blow in the Stanton test cannot be exactly calculated. With a 2 inch fall, the 5½ pound hammer is calculated by Gibson, (165) using the usual formula for bending without correction for localized stress due to the notch, to exert a fiber stress of about 95,000 pounds per square inch. Since the presence of a notch may readily multiply the calculated stress by 3 to 6, it is plain that the Stanton test made with the usual height of fall utilizes a localized stress well above the yield point of any steel, if not above the tensile strength.

It is stated (166) that at the American Rolls-Royce automobile plant a Stanton machine is used, testing up to at least "5500 impacts to determine reliability under driving conditions." Brinell tests are used for further information.

Miller (167) says "The strength of heat-treated steel depends on its resistance to permanent deformation and on its resistance to complete fracture after deformation has begun, or, in simple terms, on its hardness and toughness. These two properties are very usefully indicated by two simple tests, the Brinell test and the notched-bar impact test. . . . The notched impact test can detect brittleness where other tests do not. . . . Resistance to deformation or hardness appears to be the most important property to have in steels for resisting fatigue breakdown in automobiles. Unfortunately, great hardness is usually associated with lack of toughness, a certain amount of which latter is necessary. . . ."

The results of a Stanton machine appear to confirm results in actual practice. Miller advocates testing at a number of heights of fall of the tup, but says that a 2 inch fall gives useful results on steels. Most alloy steels, properly heat-treated to Brinell hardness of 250-300, give, he says, Stanton tests of 6,000 to 8,000. From 300 to 420 Brinell the tests run from 8,000 to 12,000, but when hardened above that figure the Stanton

tests decrease, 0.30 per cent.-0.50 per cent. C alloy steels at 500 Brinell withstanding about 2,000 blows. With lighter blows than that of the 2 inch fall the harder steels do not show so much diminution in toughness. Case-hardening strengthens the outer part of a piece which is highly stressed in bending, and a tough core resists fracture. A 3.5 per cent. Ni, 0.20 per cent. C steel case-hardened to a depth of 0.06 inch, quenched from 815° C. (1500° F.) in oil withstood 30,000 blows with a 2 inch fall, and 300,000 with a 1 inch fall. The best result at a 1 inch fall on steels not case-hardened was about 50,000.

In the discussion of a paper on fatigue by Professor H. F. Moore before the New York Section of the American Society for Steel Treating, April 25, 1922, Dr. J. A. Mathews stated that the endurance limit found by endurance tests does not tell the whole story, as it does not show ability to withstand sudden overloads and that the Stanton test has been found to give data of practical value, and in combination with the Brinell test to be a rapid method of judging the value of a steel for automotive use.

Aitchison [10, p. 308] quotes Stanton as stating that the Stanton machine should be used with such a height of fall that fracture occurs in less than 500 blows, when the results are comparable to those of single-blow notched-bar tests, or else at such a height that over 100,000 blows are required for fracture, when the results are of the order of fatigue tests, and that it is practically impossible to interpret the results of tests, frequently made during the war, in which fracture was produced in 4,000 to 6,000 blows.

Batson and Hyde [168, p. 320] make the same statements that Aitchison does and give Stanton test curves for blows of varying energy for "correctly and incorrectly heat-treated boiler plate" in which, at the same energy, the "correctly treated" specimens show longer lives than the "incorrectly treated" pieces up to 1,500 blows; but at lower blow energies the curves cross so that the "incorrectly" treated one breaks at 5,870 blows, for a given energy, while the "correctly" treated one breaks at 3,885 blows.

McAdam [47] has designed an impact-endurance testing machine quite similar in principle to the Stanton, and finds that unless the energy of impact is as great as to cause fracture in less than a million blows, the endurance of the notched bar depends not on the impact properties as shown by a single-blow test, but on the endurance limit, while with a range from 100 to 100,000 blows the slopes of the repeated-impact curves bear only a rough relationship to the single-blow test results. He also concludes that the short-life end of the repeated-impact plot of intensity of blow against life depends on the impact properties, and the long-life end, on the endurance properties.

The real value of single-blow or repeated-blow impact tests (when

the latter are made at a single height of fall and a definite weight of hammer) probably rests in the fact that the slopes of the impact-draw temperature curves (and often of the impact-chemical composition curves) are very steep, over most of the range, and, hence that, in certain ranges, they are more delicate tests for absolute uniformity of heat-treatment than some of the other mechanical tests. If then, one knows the average impact or repeated-impact value for a given steel at a given heat-treatment, slight variations in heat-treatment or chemical composition that would be only slightly apparent on other mechanical tests, or by microscopic examination, may be made evident. When the impact values are near the crest of the curve (when this shows a maximum) this delicacy is lost. But under definite conditions the results may be of great value to the works metallurgist trying to produce an absolutely uniform product.

Without full information as to the average impact value for a given material in relation to other physical properties, to chemical composition and heat-treatment an Izod value of 40 foot pounds or a Stanton figure of 7,000 blows means nothing whatever to the designing engineer. The fuller the accompanying information, the more useful the figures become.

Value of Endurance Tests

Inasmuch as many failures of steel in service under repeated stress occur at stresses far below the static proportional limit, endurance tests are of very great importance to designers of structures of machine parts subjected to repeated stress. Aitchison's statement that [10, p. 138] the proof load, the impact test, and the endurance limit are the three essential criteria by which an engineer should judge steel, has already been quoted. He also states [169] [170] that 95 per cent. of broken automobile parts have failed through fatigue.

Hoyt [15, pp. 204, 233] criticizes endurance tests because brittle material, for example, steel with high phosphorous content, may give high results.

Mathews quotes [17] Dr. T. E. Stanton, of the National Physical Laboratory of England, as follows: "There can be no doubt that the maximum range of stress of an unlimited number of repetitions is the most valuable strength characteristic of a material which the designer of structures or machines can possess. The test does not attempt to discriminate between brittle and tough materials, which is of course the function of impact testing."

Moore and Jasper [172, p. 56] also emphasize the fact that no single test can give an index of the usefulness of a material for all classes of service. That the endurance limit bears no relation to the ductility or the resistance to impact indicates that the qualities indicated by the tests are not the same.

Jenkin (162, p. 8) says, "it can no longer be doubted that the life of all parts which are subject to alternating or fluctuating stresses (such as most engine parts and those aeroplane parts which are subject to vibration) depends simply on the fatigue range of the material they are made of."

The authors believe that one of the most valuable results of the recent exhaustive studies of endurance testing, notably by Moore (173) and McAdam, (47) has been to produce evidence of the extremely detrimental effect exerted by anything which acts to raise the local stress over the stress computed by ordinary engineering calculations. Sharp corners, fillets of too small radius, surface scratches or notches, and flaws or inclusions which may act as internal notches are causes of grave danger. Their effect is difficult or impossible of exact calculation, hence they must be guarded against with the greatest care.

Moore and Kommers, (173) and Moore and Jasper, (172) McAdam, (47) Bairstow, (175) and Batson and Hyde (168) all present direct evidence on this point, the last named investigators stating: "There seems to be no doubt that many fatigue failures attributed to faulty material are really due to unsuitable fillets, sharp corners or surface scratches left during machining." Jenkin (162, p. 12) goes into this subject deeply. He shows, for example, that the effect of adding serrations to a shaft (by comparing a castellated shaft with a similar shaft of diameter equal to the diameter at the base of the castellation) reduces its strength to one-half. Wilson and Haigh (176, 283) also deal with another phase of the subject.

A remarkable proportionality is found by all endurance workers (who use test-pieces of such form that local concentration of stress does not vitiate the stress calculations) between tensile strength and endurance limit or between Brinell hardness and endurance limit, practically all types of the softer engineering steels showing endurance limits in reversed bending within 45 per cent. to 55 per cent. of the tensile strength (endurance range from 90 to 110 per cent.). Considering the difficulties inherent in endurance testing and the ordinary deviations found in tensile tests of duplicate specimens, the differences between the endurance limit usually found by experiment and that calculated from a tensile test or even a Brinell test, are almost within the errors inherent in the methods of testing.

The question at once arises whether endurance testing can be dispensed with and reliance placed on tensile or Brinell tests as a basis for engineering design in which steel is used to resist repeated stress.

This focuses attention on the cases in which the endurance limit of a material does not follow the usual ratio, or in which individual specimens show unexpectedly low results.

Internal stresses, such as quenching stresses insufficiently relieved, (172, p. 61; 10, p. 208) tend to give a low endurance ratio. Lessels (262) points out

that the presence of internal stress lowers the endurance limit. He suggests that the ratio of elastic limit to yield point gives a factor by which the endurance limit may be calculated from the tensile strength, for steels of a given class of micro-structure. Lessels defines (231) elastic limit as the stress at the first deviation from a straight line stress-strain relation, and yield point as the stress causing an extension of 0.01 inch on a 2 inch gage length.

The use of such a correction factor is probably a step in the right direction but methods of determining endurance limit by calculation fail to recognize the profound effect on endurance limit exerted by inhomogeneities in the metal. These exert but little or no effect in the tensile test.

McAdam (47) finds that it is "probable that non-metallic inclusions in steel have a decided effect in lowering the endurance ratio." His comparative endurance tests on specimens taken longitudinally and transversely bear out this theory. Moore and Jasper (172, p. 91) say "It seems reasonable to suppose that internal flaws act to weaken metal under repeated stress in a manner similar to the action of external notches." And in their most recent report they state (174) that the behavior of a piece of dirty steel is a matter of chance; it may act as well as a clean piece, or it may show up much more poorly.

Mathews (177) says: "Freedom from internal flaws and surface irregularities is far more important in members subjected to but few repetitions of load. Mathews continually emphasizes the necessity for freedom from non-metallic inclusions for greatest reliability of steel.

Templin (178) finds that, in endurance testing of aluminum alloys, seams, flaws, inclusions of foreign matter, or segregation of constituents will cause premature failure of the test specimen.

Lea (179) points out that a slag inclusion or similar internal defect tends to act, under repeated stress, as if it were a crack already started before the test began, *i.e.*, it causes more rapid failure than if the specimen were sound.

A case that is probably in point is that of annealed "screw stock" with 0.09 per cent. sulfur, tested by Moore. (173, pp. 67-83) Although two tests at about 29,000 and 28,000 pounds per square inch withstood 60 million cycles without fracture, another specimen, stressed only to 25,000 pounds per square inch broke after 3¼ million cycles. Screw stock is known to contain large numbers of manganese sulfide inclusions and it seems likely that the specimen giving the low result happened to have an inclusion so located in the stressed portion of the bar that it acted as an internal notch. Sisco (315) makes a similar comment on the effect of sulfides.

Haigh (180) says: "A low ratio of fatigue limit to the ultimate strength is almost always due to slag inclusions or dirtiness of the metal." Haigh

(283) has recently elaborated this argument. Fremont (303) is of the same opinion.

It is significant that those who have done the most work on endurance testing should thus emphasize the necessity for clean steel.

Dynamic tests therefore may test not only the inherent properties of the steel but also the quality of the steel-making. Since chance is so largely involved because of the localized nature of the test and the opportunity for the maximum stress to fall on either a clean or a dirty area, the results will generally be somewhat less concordant than those of static tests.

Chapter 7.

Tensile and Impact Test Data for Molybdenum and Cerium Steels.

The series of steels selected for the authors' tests are described in Tables 11 and 12, and full data as to chemical analysis, details of rolling, and of heat-treatment are given in Appendix A. Specimens were studied by tensile, Brinell, Izod, Stanton and Upton-Lewis tests. Results of these tests are included in Tables 11 and 12, and are represented graphically in Figs. 24 to 40.

For comparison of results the steels tested have been grouped as follows:

A_1—Steels with but one alloying element, (molybdenum, cerium or vanadium).

A_2—Steels of high manganese content, molybdenum as added alloying element.

B.—Steels with molybdenum content above 1 per cent.

C_1.—Steels of about 1 per cent. chromium, with molybdenum, cerium, or vanadium.

C_2.—Steels of varying carbon, chromium and molybdenum content.

D.—Steels of 1.25 per cent. nickel, 0.75 per cent. chromium, with molybdenum, cerium, or vanadium.

E.—Steels of 2.50 per cent. nickel, 0.90 per cent. chromium, with molybdenum, cerium, or vanadium.

F.—Cerium steels, low in manganese.

Groups A_1 and A_2

Heat-treated Steels Nos. 1, 2, 3, 5, 6, 7, 8, 55.

In Group A_1 the first three steels are plain carbon steels, one with about 0.35 per cent. molybdenum and one with about 0.70 per cent. molybdenum. Steel No. 5, with about 0.50 per cent. cerium, should be compared with these. The three steels of Group A_2 differ from these only in slightly higher carbon content, and in having the manganese content increased from about 0.75 per cent. to 1.05 per cent.-1.29 per cent.

The steels of normal manganese content were water-quenched, those of higher manganese content were oil-quenched. In Fig. 24 tensile proper-

TABLE 11

MECHANICAL TEST DATA ON ROLLED RODS

Group	Steel No.	Draw No.	Composition (Per Cent) C	Ni	Cr	Mo	V	Ce	Heat Treatment Quench °C.	Medium	Draw °C.	Tensile Data: Brinell Hardness	Prop. Lim. lbs./sq. in.	Yield Point Extensometer	Yield Point Drop Beam	Maximum Tensile Strength Orig. Area	Elong., % in 2"	Red. Area Neck %	Red. Area Fracture %	Merit Index[a]	Elastic Ratio	Breaking Strength Orig. Area	Breaking Strength Red. Area	Nature of Fracture	Impact Data: Brinell Hardness Stanton Specimen	Stanton Blows to Fracture	Brinell Hardness Izod Specimen	Izod Test ft. lbs.	Endur. Data: Brinell Hardness Endurance Specimen[c]	Endur. Limit Upton-Lewis test lbs. sq. in.[b]	Remarks
A1	1	1	.40	....	....	....	....	....	870	W	300	445	S[c]	183,000	N[d]	225,000	6.5	17.0	16.5	16	81	210,750	260,000	C[e]	435	6310	(440)[f]	10	N.B.[g]	....	
	1	2	....	....	....	....	....	....	do.	W	360	405	S	170,000	N	193,500	8.7	30.7	26.3	23	88	173,500	234,000	C	400	8440	(380)	14.5	N.B.	....	
	1	3	....	....	....	....	....	....	do.	W	420	375	S	135,000	N.D.[h]	171,500	12.5	40.3	36.9	32	79	N.D.	N.D.	C	350	6300	(350)	31.5	325	68,000	
	1	4	....	....	....	....	....	....	do.	W	425	N.B.	......	......	......	......	....	....	....	....	....	......	......	....	N.B.	....	N.B.	....	340	78,000	
	3	1	.38	....	....	.37	....	....	do.	W	300	450	S	190,000	N	224,000	11.0	43.3	41.3	40	85	169,750	288,000	C	420	6025	(430)	15.5	480	U[i]	
	3	2	....	....	....	....	....	....	do.	W	360	420	S	185,000	N	207,750	12.0	49.1	44.4	46	89	149,750	270,000	C	385	6850	(400)	15.5	380	96,000	
	3	3	....	....	....	....	....	....	do.	W	420	375	S	170,000	N	187,500	13.5	51.9	50.6	53	91	149,000	264,000	C & Serrated	340	6890	(360)	26	360	85,000	
	3	N1	....	....	....	....	....	....	900	air	....	200	60,000	65,500	67,500	107,500	24.0	54.0	51.0	45	61	81,300	166,000	C	(200)	1625	(200)	22	N.B.	....	Stanton test 1624–1339
	3	N2	....	....	....	....	....	....	840	do.	....	210	60,000	65,500	65,500	104,000	25.0	54.5	53.0	47	63	80,000	170,000	C	205	1480	190	27	180	50,000	
	2	1	.41	....	....	.67	....	....	870	W	300	N.B.	......	......	......	......	....	....	....	....	....	......	......	....	N.B.	....	N.B.	....	480	U	
	2	2	....	....	....	....	....	....	do.	W	360	425	S	190,000	N	223,250	12.5	51.9	45.9	54	85	158,250	293,000	C	420	7565	(420)	17.5	445	U	
	2	3	....	....	....	....	....	....	do.	W	420	390	S	185,000	N	198,500	13.5	51.9	49.4	54	93	136,500	269,000	C	390	6430	(390)	22.5	420	91,000	
	2	4	....	....	....	....	....	....	do.	W	500	370	S	160,000	N	178,250	14.5	54.5	47.9	54	90	129,500	249,000	C	340	5800	(360)	28	370	92,000	
	2	N1	....	....	....	....	....	....	900	air	....	230	50,000	62,500	N.D.	121,500	16.0	46.5	45.8	28	51	99,500	183,000	C	230	1520	(230)	11.5	N.B.	....	Stanton tests 2268–2069
	2	N2	....	....	....	....	....	....	840	air	....	230	67,500	71,000	N.D.	119,000	21.0	51.5	50.8	41	60	92,000	187,000	C	230	2170	230	14	225	54,000	
A2	6	1	.44	....	....	....	....	....	875	oil	350	395	S	160,000	N	209,000	7.0	17.0	16.6	16	77	195,000	234,000	C	(400)	6150	(400)	10.5	415	U	
	6	2	....	....	....	....	....	....	875	oil	400	380	S	150,000	N	187,000	8.5	24.0	23.0	19	80	171,000	222,000	C	(385)	7600	(385)	15	385	89,000	
	6	3	....	....	....	....	....	....	875	oil	450	330	S	135,000	N	168,750	11.0	34.0	30.2	25	80	148,500	213,000	C	(350)	6790	(350)	27	375	85,000	
	8	1	.44	....	....	.34	....	....	875	oil	375	430	S	185,000	N	220,250	11.0	37.2	35.5	36	84	177,250	275,000	C	(425)	6050	(425)	9	425	U	Group A2 has high Mn. #6, 1.05% #8, 1.29% #7, 1.24%
	8	2	....	....	....	....	....	....	875	oil	450	400	S	170,000	N	194,750	11.5	37.2	35.3	34	87	159,250	247,000	C	(390)	7890	(390)	15	385	98,000	
	8	3	....	....	....	....	....	....	875	oil	525	340	S	145,000	N	170,000	15.0	40.3	40.2	40	85	140,000	234,000	C	(340)	6440	(340)	36.5	340	U	
	7	1	.43	....	....	.73	....	....	875	oil	400	430	S	180,000	N	221,500	13.0	49.1	46.8	52	81	160,000	300,000	C & Serrated	(430)	9010	(430)	16	430	U	
	7	2	....	....	....	....	....	....	875	oil	475	395	S	160,000	N	193,250	14.5	51.9	47.0	53	83	143,000	270,000	C & Serrated	(390)	7200	(390)	20.5	385	96,000	
	7	3	....	....	....	....	....	....	875	oil	550	370	S	157,000	N	181,750	17.0	49.1	46.8	57	86	139,250	262,000	C & Serrated	(370)	5800	(370)	32	370	85,000	
B	41	1	.46	....	....	1.05	....	....	900	oil	425	420	S	190,000	N	219,000	11.7	43.3	40.0	41	87	N.D.	N.D.	C	(420)	8050	(420)	29.5	430	98,000	j
	41	2	....	....	....	....	....	....	900	oil	500	405	S	185,000	N	201,750	13.7	46.2	43.8	50	91	N.D.	N.D.	C	(390)	8840	(390)	36	385	96,000	j
	41	3	....	....	....	....	....	....	900	oil	600	400	S	180,000	N	194,500	16.0	49.1	46.9	59	92	N.D.	N.D.	Serrated	(390)	6185	(390)	36	385	96,000	j
	41	N	....	....	....	....	....	....	900	air	....	280	S	75,000	N	140,000	17.5	43.3	42.9	32	54	N.D.	N.D.	C	280	1500	(280)	7	290	74,000	j

[a], etc. See notes, p. 129.

TABLE 11 (Continued)

Group	Steel No.	Draw No.	Composition (Per Cent) C	Ni	Cr	Mo	V	Ce	Heat Treatment Quench °C.	Medium	Draw °C.	Tensile Data: Brinell Hardness	Prop. Lim. lbs./sq. in.	Yield Point Extensometer	Yield Point Drop Beam	Maximum Tensile Strength Orig. Area	Elong., % in 2"	Red. Area Neck %	Red. Area Fracture %	Merit Index [a]	Elastic Ratio	Breaking Strength Orig. Area	Breaking Strength Red. Area	Nature of Fracture	Impact Data: Brinell Hardness Stanton Specimen	Stanton Blows to Fracture	Brinell Hardness Izod Specimen	Izod Test ft. lbs.	Endur. Data: Brinell Hardness Endurance Specimen	Endur. Limit Upton-Lewis test lbs. sq. in.[b]	Remarks
B	43	X	.39			1.90			775	oil	550	330	S	130,000	N.D.	159,750	13.0	42.2	41.0	34	81	130,000	220,000	C	290	4070	(300)	26	N.B.	....	
	43	Y							775	oil	650	240	S	98,000	N.D.	112,250	22.0	59.8	56.8	58	87	N.D.	N.D.	C	230	2100	(235)	53	N.B.	....	
	43	Z							925	W	650	275	S	125,000	N.D.	139,000	17.0	54.5	52.0	50	90	N.D.	N.D.	Star	270	3665	......	....	N.B.	....	Izod bar cracked in quenching
	43	N							900	air	....	275	S	75,000	N	141,500	16.5	35.2	32.0	28	53	N.D.	N.D.	C	300	2450	(280)	7	N.B.	....	
	43	1							900	oil	425	N.B.	......	......	......	......	....	....	....	....	....	......	......	....	N.B.	....	N.B.	....	430	94,000	*i*
	43	2							900	oil	600	N.B.	......	......	......	......	....	....	....	....	....	......	......	....	N.B.	....	N.B.	....	420	94,000	*i*
	43	4							900	oil	650	N.B.	......	......	......	......	....		....	....	....	......	......	....	N.B.	....	N.B.	....	270	69,000	First drawn at 500°, Brinell 420; redrawn at 650° *i*
	42	X	.36			2.05			875	oil	550	430	S	187,500	N	210,500	14.0	49.1	45.0	55	88	N.D.	N.D.	Serrated	N.B.	....	430	27	N.B.	....	
	42	Y							875	oil	650	275	S	130,000	N.D.	139,000	19.0	57.3	56.0	60	93	92,500	210,000	Star	285	3310	270	51	N.B.	....	
	42	Z							925	W	545	N.B.	......	......	......					....	....	......	......	....	420	5180	420	28	N.B.	....	
	42	N							900	air	...	275	S	75,000	N	143,250	20.0	49.1	45.0	43	52	N.D.	N.D.	C	285	2575	260	11	N.B.	....	
	44	1	.36			3 00			900	oil	425	430	S	200,000	200,000	217,500	10.5	39.4	36.0	36	92	176,000	275,000	C & Serrated	420	8770	(425)	12.5	420	104,0 00	
	44	2							900	oil	500	415	S	190,000	195,000	198,250	13.5	41.9	40.4	45	96	156,000	261,000	C & Serrated	420	7300	(415)	20	420	108,000	
	44	3							900	oil	575	355	S	166,000	167,000	176,500	14.5	46.8	45.6	39	93	136,000	250,000	C & Serrated	N.B.	....	N.B.	....	370	115,000	
	44	(N-A)							900	(K)	....	205	S	67,500	N	112,500	22.5	39.3	37.5	33	60	N.D.	......	C	195	392	(200)	6	N.B.	....	
	39	1	.50			1.15			850	oil	425	475	S	215,000	N	249,250	9.5	31.2	30.2	32	86	176,500	253,000	C	475	4225	(475)	12.5	N.B.	....	
	39	2							850	oil	525	435	S	195,000	204,000	225,750	13.0	38.3	34.8	44	87	156,000	240,000	C & Serrated	445	4810	(440)	19	N.B.	....	
	39	3							850	oil	625	420	S	195,000	205,000	217,000	13.0	42.6	40.4	47	90	136,000	228,000	C & Serrated	N.B.	....	(420)	29.5	N.B.	....	
	39	N							900	air	....	295	S	75,000	N	149,000	19.5	41.4	38.9	38	50	N.D.	......	C	295	521	(295)	9	N.B.	....	
	40	1	.65			1.90			825	oil	550	455	S	210,000	225,000	236,000	8.5	30.7	27.5	27	89	208,000	287,000	C	450	3610	(450)	13	N.B.	....	
	40	2							825	oil	650	365	S	147,000	N	164,700	10.0	43.3	40.8	27	89	143,000	242,000	C	325	3625	(345)	25	N.B.	....	
	40	(N-A)							870	(K)	....	300	S	70,000	N	152,000	14.5	37.2	34.3	26	46	N.D.	......	C	300	209	295	6	N.B.	....	
	5	1	.38					.50±	870	W	300	395	S	175,000	N	211,750	10.0	37.2	34.6	31	83	169,000	259,000	C	(395)	9950	(395)	19.5	N.B.	....	Izod varies 14 to 27
	5	2							870	W	360	360	S	165,000	N	182,500	11.5	46.2	41.1	37	91	141,000	240,000	C	(360)	7030	(360)	41.5	365	80,000	Izod varies 33 to 50
	5	3							870	W	420	310	S	135,000	N	154,750	15.5	54.5	49.5	49	88	111,000	220,000	C	(310)	5435	(310)	52	300	70,000	Izod varies 40 to 64

B	55	1	.50				.20		840	oil	475	335	148,000	155,000	156,000	171,500	15.5	55.0	54.4	56	91	116,500	255,000	Star	375	4610	365	44.5	360	80,000	
	55	2							840	oil	555	305	140,000	142,000	144,000	147,000	17.0	53.9	53.1	57	96	105,500	225,000	Stardiag brk.	320	3340	320	58.5	310	75,000	
	55	N							900	air		260	95,000	96,000	97,000	125,000	25.0	54.0	52.9	60	76	93,500	197,000	C	270	1980	230	19	250	65,000	
	55	A							(850	anne	aled)	195	70,000	70,000	70,000	100,000	29.5	53.2	52.7	52	70	79,500	168,000	C	185	1110	175	33.5	N.B.		
Cr	9	X	.35		.94				900	oil	225	N.B.													N.B.		475	13	N.B.		
	9	1							900	oil	425	415	S	160,000	N	194,500	12.0	40.6	37.2	35	82	152,750	243,000	C	(400)	8250	(400)	23	385	78,000±	
	9	2							900	oil	525	340	S	131,000	N	158,000	16.5	54.5	51.8	52	83	116,000	241,000	C & Serrated	(325)	5340	310	55	320	80,000	
	9	3							900	oil	625	270	S	105,000	110,000	126,750	22.5	64.7	62.2	74	83	83,250	219,000	Star	(260)	3300	(260)	90	255	57,000	
	45	1	.40		.88	.30			820	oil	425	420	S	170,000	N	202,500	12.0	47.6	44.4	43	84	N.D.	N.D.	C	445	9370	445	8	420	98,000	Another lot of endurance bars—900° oil, 525° Brinell 350, gave endurance limit 85,000
	45	2							820	oil	525	330	S	143,000	N	166,250	15.0	52.8	51.5	49	86	N.D.	N.D.	C & Serrated	385	6475	375	26	360	87,000	
	45	3							820	oil	625	290	S	111,500	118,000	133,500	21.0	65.5	65.5	75	84	N.D.	N.D	Star	320	4225	300	58	300	70,000	
	45	N							900	air		245	S	60,000	N	127,000	17.3	50.1	48.4	33	47	N.D.	N.D.	C	N.B.		N B.		N.B.		
	11	X	.41		.89	.36			900	oil	225	N.B.													N.B.		475	20	N.B		
	11	1							900	oil	425	395	S	170,000	N	201,500	12.0	49.1	42.5	44	84	151,750	263,000	C	(410)	8500	(410)	22	420	U	
	11	2							900	oil	525	375	S	155,000	N	178,200	14.7	51.9	48.6	51	87	132,400	257,000	C & Serrated	(370)	5600	(370)	33.5	365	85,000	
	11	3							900	oil	625	265	S	112,000	125,000	140,250	19.0	62.3	61.6	62	80	92,100	240,000	Star	(270)	4110	(270)	71	270	U	
	11	N_1							900	air		280	50,000	57,500	N	129,500	18.0	45.5	44.2	31	44	105,500	189,000	C	(280)	1815	(280)	7.5	N.B.		
	11	N_2							840	air		250	47,500	57,500	N	129,500	16.5	44.0	43.1	28	44	108,000	190,000	C	(245)	2445	(245)	12	240	65,000	Stanton tests, 2635, 2312
	10	X	.40		.95	.68			900	oil	225	N.B.													N.B.		495	23	N.B.		
	10	1							900	oil	425	425	S	170,000	N	219,000	12.0	43.3	41.4	41	78	166,000	283,000	C	(420)	8600	(420)	19	400	97,000	
	10	2							900	oil	525	390	S	165,000	N	203,500	13.0	46.2	42.8	45	81	159,000	278,000	C	(390)	6740	(390)	33.5	385	85,000±	
	10	3							900	oil	625	350	S	145,000	N	174,000	15.0	51.9	50.5	50	83	127,000	256,000	C & Serrated	(345)	6300	(345)	43	340	89,000	
	10	N_1							900	air		320	30,000	47,500	N	160,000	5.0	4.5	4.5	9	30	160,000	167,500	Flat	(320)	2275	(320)	7.5	N.B.		
	10	N_2							820	air		285	25,000	38,500	N	148,500	15.0	20.0	20.0	18	26	138,500	173,000	Flat	300	1640	275	6	255	67,000	Stanton tests, 1948, 1336
	12	X	.40		.93		.20		900	oil	225	N.B.													N.B.		495	26	N.B.		
	12	1							900	oil	425	400	S	160,000	N	193,000	11.7	49.1	46.3	40	83	142,000	265,000	C	(410)	8675	(410)	21	420	98,000	
	12	2							900	oil	525	360	S	152,500	156,500	164,500	16.7	54.5	54.4	58	93	112,500	247,000	Star	(350)	5730	(350)	42	340	79.000	
	12	2R							900	oil	525	350	140,000	145,000	150,000	156,000	16.8	53.4	52.5	54	93	109,500	230,000	Star	N.B.		N.B.		N.B.		
	12	3							900	oil	625	305	S	130,000	137,500	145,750	17.8	58.0	56.5	59	89	102,000	234,000	Star	(280)	3825	(280)	57	255	62,000	
	12	N							900	air		245	S	80,000	82,500	113,500	21.5	62.3	56.8	55	71	77,000	178,500	C	(245)	1520	(245)	33.5	N B.		
	12	A							(825	anne	aled)	150	S	50,000	50,000	80,000	36.0	64.7	63.1	67	63	60,000	162,500	C	(150)	1230	(150)	66.5	N.B		
	57	1	.41		.93		.16		900	oil	425	400	175,000	190,000	N	208,500	13.0	46.5	44.0	48	91	152,500	272,000	Star	N.B.		N.B.		420	88,000	
	57	2							900	oil	525	350	165,000	167,500	172,500	183,500	14.0	46.5	44.0	45	91	140,000	251,000	Star	N.B.		N.B.		350	74,000	
	57	3							900	oil	625	300	137,500	142,500	144,000	154,500	17.0	52.0	(1)	53	92	109,000	(1)	Star	N.B.		N B.		285	74,000	
	57	N							900	air		235	85,000	91,000	94,500	126,000	22.5	62.5	61.9	65	72	83,500	119,000	C	240	2360	245	36	225	66,000	
	13	X	.41		.98			.33±	900	oil	225	B.N.													N.B.		510	19	N.B.		
	13	1							900	oil	425	440	S	175,000	N	211,250	11.0	40.3	38.3	35	83	164,250	267,000	C	(430)	5450	(430)	11	420	U	
	13	2							900	oil	525	280	S	125,000	135,000	148,250	16.5	53.3	51.8	48	84	103,000	214,000	C & Serrated	(290)	5150	(240)	35	300	U	
	13	3							900	oil	625	265	S	100,000	105,000	122,250	17.2	57.3	54.6	45	82	91,250	201,000	C & Serrated	(250)	2970	(250)	54	230	U	
	14	X	.41		.98			.45±	900	oil	225	N.B.													N.B.		495	13	N.B.		
	14	1							900	oil	425	445	S	185,000	N	217,750	9.0	30.7	29.7	26	85	160,000	228,000	C	(430)	5200	(430)	12.5	410	84,000	

TABLE 11 (Continued)

			Composition (Per Cent)						Heat Treatment			Tensile Data													Impact Data				Endur. Data		Remarks
Group	Steel No.	Draw No.	C	Ni	Cr	Mo	V	Ce	Quench °C.	Medium	Draw °C.	Brinell Hardness	Prop. Lim. lbs./sq. in.	Yield Point Extensometer	Yield Point Drop Beam	Maximum Tensile Strength Orig. Area	Elong., % in 2"	Red. Area Neck %	Red. Area Fracture %	Merit Index [a]	Elastic Ratio	Breaking Strength Orig. Area	Breaking Strength Red. Area	Nature of Fracture	Brinell Hardness Stanton Specimen	Stanton Blows to Fracture	Brinell Hardness Izod Specimen	Izod Test ft. lbs.	Brinell Hardness Endurance Specimen	Endur. Limit Upton-Lewis test lbs. sq. in.[b]	
C_1	14	2	...	...	...	...	...	...	900	oil	525	325	S	130,000	N	149,500	17.0	54.5	51.2	52	87	108,500	222,000	C & Serrated	(320)	4150	(320)	40	310	72,000	
	14	3	...	...	...	...	...	...	900	oil	625	245	S	90,000	100,000	119,500	22 0	59.8	58.2	57	75	86,250	206.500	C & Serrated	(240)	2770	(240)	52	240	59,000	
C_2	47	1	.15	...	.73	.28	...	...	925	W	425	320	S	125,000	135,000	155,500	14.0	55.5	51.5	44	80	N.D.	N.D.	C	300	5400	320	53	310	61,000±	
	47	2	...	...	...	...	...	...	925	W	525	285	S	105,000	115,000	126,250	18.5	63.9	61.5	59	83	N.D.	N.D.	C	280	4240	270	79	275	69,000	
	47	3	...	...	...	...	...	...	925	W	630	215	S	77,500	80,000	97,000	25.5	78.6	73.4	98	78	N.D.	N.D	C	195	1840	185	117	200	52,000	
	46	1	.22	...	.79	.34	...	...	850	W	425	330	S	N.D.	124,000	137,000	13.5	52.0	48.7	N.D	N.D.	N D.	N.D.	C	365	5820	340	32	345	80,000	
	46	2	...	...	...	...	...	...	850	W	525	320	107,500	110,250	126,000	135,500	18.0	63.0	61.0	60	81	84,500	228,000	C & Serrated	300	3840	300	56	310	75,000	
	46	3	...	...	...	...	...	...	850	W	625	260	S	90,000	104,500	116,000	22.5	69.1	66.0	75	78	N.D.	N.D.	C & Serrated	260	3090	240	81	235	57,000	
	46	N	...	...	...	...	...	...	900	air	....	205	S	N.D.	86 000	98,000	21.5	60.0	58.2	N.D.	N.D.	N.D.	N.D.	C	N.B.	....	......	....	.....	....	
	49	1	.25	...	.95	.73	...	...	925	oil	425	400	S	150,000	N	187,750	15.0	56.4	52.0	58	80	N.D.	N.D.	C	(385)	8160	385	33	375	86,000	
	49	2	...	...	...	...	...	...	925	oil	530	365	S	140,000	N	165,250	19.0	62.2	60.7	78	85	N.D.	N.D	C & Serrated	(365)	6450	365	59	365	U	
	49	2R	...	...	...	...	...	...	925	oil	525	385	147,500	155,000	N	175,000	19.0	57.5	55.0	74	88	117,000	260,000	Star	N.B.	....	N.B.	....	345	81,000	
	49	3	...	...	...	...	...	...	925	oil	600	320	126,000	131,000	140,000	150,000	20.0	66.0	64.6	83	87	N.D.	N.D.	Star	N.B.	....	N.B.	....	300	72,000	
	49	3R	...	...	...	...	...	...	925	oil	630	250	S	100,000	105,500	119,500	22.0	71.3	68.6	84	84	N.D.	N.D.	C & Serrated	(265)	2740	240	95	300	U	
	48	1	.42	...	.55	.39	...	...	925	oil	425	420	S	187,500	N	207,000	14.0	51.5	49.3	54	91	N.D.	N.D.	C	(400)	6660	430	21	375	95,000	Another set of endurance bars
	48	2	...	...	...	...	...	...	925	oil	530	365	S	162,500	N	174,750	17.0	55.3	53.7	64	93	N.D.	N.D.	C & Serrated	(360)	6820	350	51	365	92,000	350 Brinell gave 90,000 end. limit
	48	2R	...	...	...	...	...	...	925	oil	525	385	162,500	170,000	N	184,500	14.0	41.5	37.5	42	92	150,000	251,000	C & Serrated	N.B.	....	N.B.	....	N.B.	....	
	48	3	...	...	...	...	...	...	925	oil	630	255	S	122,500	125,000	130,000	20.0	64.7	61.5	72	94	N.D.	N.D.	C & Serrated	(280)	2975	250	95	300	79,000	
	48	N	...	...	...	...	...	...	900	air	....	250	S	72,500	N	122,250	17.0	45.5	42.6	30	59	N.D.	N.D.	C	(250)	2515	(250)	20	N.B.	....	
	48	A	...	...	...	...	...	...	(825	anne	aled	) 180	S	57,500	59,750	97,000	24.5	43.3	39.8	33	59	N.D.	N.D.	C& Granular	(180)	1450	(180)	30.5	N.B.	....	
	50	1	.52	....	.95	.39	...	......	815	oil	425	400	S	170,000	N	209,250	13.0	47.9	44 2	48	81	N.D.	N.D.	C & Serrated	420	7200	(420)	16	445	100,000	Endurance bar quenched from 840° oil, draw temperatures same as other bars

C	50	2	...	...	...	...	...	...	815	oil	525	365	S	155,000	159,000	188,250	17.5	53.9	(1)	65	82	N.D.	N.D.	C & Serrated	365	6510	(365)	19	380	92,000±	
	50	3	...	...	...	...	...	...	815	oil	625	285	S	100,000	105,500	135,000	19.5	55.7	51.5	52	74	N.D.	N.D.	C & Serrated	310	3900	(285)	72	255	60,000	
	50	N	...	...	...	...	...	...	900	air	...	300	S	50,000	N	153,500	12.0	28.0	28.0	17	33	N.D.	N.D.	Flat	320	1000	(310)	5	N.B.	...	
D	15	X	.47	1.23	.65	...	...	...	825	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	510	9	N.B.	...	
	15	1	...	...	...	...	...	...	825	oil	420	420	S	180,000	184,500	202,500	13.0	51.9	46.6	44	89	145,500	273,000	C	(420)	7420	(420)	22	N.B.	...	
	15	2	...	...	...	...	...	...	825	oil	525	345	S	145,000	147,250	159,500	15.5	54.5	50.9	53	91	117,250	239,000	C & Serrated	(330)	5270	(330)	47	320	83,000	
	15	3	...	...	...	...	...	...	825	oil	625	275	S	95,000	119,000	129,750	21.7	62.3	59.5	65	73	89,750	212,000	Star	(270)	3100	(270)	76	...	...	
	17	X	.39	1.28	.68	.31	...	...	825	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	495	20	N.B.	...	
	17	1	...	...	...	...	...	...	825	oil	425	400	S	170,000	180,000	199,500	13.0	46.2	44.0	45	86	146,250	262,000	C	(400)	6875	(400)	27	N.B.	...	
	17	2	...	...	...	...	...	...	825	oil	525	355	S	155,000	160,000	168,500	15.0	54.5	54.1	53	92	117,500	256,000	C & Serrated	(350)	5870	(350)	37	340	88,000	
	17	3	...	...	...	...	...	...	825	oil	625	315	S	135,000	138,500	145,750	19.0	60.6	59.8	67	92	95,750	240,000	Star	(315)	4460	(315)	57.5	N.B.	...	
	16	X	.41	1.27	.67	.83	...	...	825	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	510	22	N.B.	...	
	16	1	...	...	...	...	...	...	825	oil	425	460	S	180,000	196,750	224,000	12.5	46.2	42.0	47	88	166,750	288,000	C	(460)	7250	(460)	16	440	100,000	
	16	2	...	...	...	...	...	...	825	oil	525	420	S	170,000	180,000	202,500	14.0	43.3	40.9	46	84	160,250	271,000	C	(420)	6620	(420)	25.5	N.B.	...	
	16	3	...	...	...	...	...	...	825	oil	625	380	S	165,000	171,500	182,500	14.5	51.9	50.6	53	90	133,250	270,000	C & Serrated	(370)	5920	(370)	34	365	74,000	
	18	X	.39	1.20	.74	...	.24	...	825	oil	225	N.B	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	510	23	N.B.	...	
	18	1	...	...	...	...	...	...	825	oil	425	400	S	185,000	186,500	195,500	11.5	49.1	49.0	43	94	139,000	270,000	C & Serrated	(400)	8230	(400)	31	N.B.	...	
	18	2	...	...	...	...	...	...	825	oil	525	340	S	150,000	156,000	160,000	13.0	54.5	51.4	45	94	116,000	239,000	Star	(330)	6085	(330)	44	320	88,000	
	18	3	...	...	...	...	...	...	825	oil	625	305	S	135,000	139,750	143,000	14.0	57.3	56.0	46	94	99,500	227,000	Star	(305)	4940	(305)	62	N.B.	...	
	20	X	.41	1.17	.77	...	...	.25	825	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	510	16	N.B.	...	
	20	1	...	...	...	...	...	...	825	oil	420	420	S	170,000	178,000	197,000	12.5	49.1	46.6	56	86	142,750	268,000	C	(420)	7265	(420)	17	N.B.	...	
	20	2	...	...	...	...	...	...	825	oil	525	310	S	130,000	134,250	149,000	17.0	54.5	54.0	52	87	105,500	230,000	C & Serrated	(305)	4120	(305)	43	300	82,000	
	20	3	...	...	...	...	...	...	825	oil	625	270	S	107,500	110,500	124,750	19.5	46.2	43.7	42	86	98,000	176,000	Star	(270)	2560	(270)	56	N.B.	...	Seam in tensile bar
	52	X	.54	1.02	.84	...	...	.39	810	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	C, not symmetrical	N.B.	...	555	9	N.B.	...	
	52	1	...	...	...	...	...	...	810	oil	420	440	S	195,000	200,250	214,000	9.0	27.4	25.6	25	91	186,500	251,000		450	4920	(435)	13	420	97,000	Tensile bar slightly seamy
	52	2	...	...	...	...	...	...	810	oil	525	345	S	145,000	149,750	161,500	16.2	46.2	44.0	46	90	127,500	228,000	C & Serrated	(330)	3345	(330)	31	315	75,000	One Stanton bar split at seam in square—centering before quenching Tensile bar slightly seamy
	52	3	...	...	...	...	...	...	810	oil	625	285	S	115,000	118,000	129,000	17.0	43.3	38.5	37	89	N.D.	...	C & Serrated	(285)	3110	(285)	46	N.B	...	Tensile bar seamy
E	21	X	.36	2.56	.83	...	...	...	810	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	495	22	N.B.	...	
	21	1	...	...	...	...	...	...	810	oil	425	375	S	175,000	176,750	191,250	14.0	54.5	52.2	53	91	129,000	271,000	C & Serrated	(375)	7390	(375)	23	N.B.	...	
	21	2	...	...	...	...	...	...	810	oil	525	310	S	140,000	144,500	151,750	17.0	57.3	55.5	56	92	101,750	228,000	Star	(305)	4720	(305)	47.5	300	68,000	
	21	3	...	...	...	...	...	...	810	oil	625	260	S	115,000	119,500	126,250	24.0	64.7	61.6	79	91	83,000	216,000	Star	(255)	3015	(255)	74	250	65,000	
	23	X	.46	2.45	.88	.35	...	...	810	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	510	21	N.B.	...	
	23	1	...	...	...	...	...	...	810	oil	425	420	S	185,000	190,750	214,000	13.0	49.1	46.9	51	87	151,750	285,000	C	410	6450	(415)	20	N.B.	...	
	23	2	...	...	...	...	...	...	810	oil	525	385	S	155,000	158,500	182,500	15.5	51.9	49.5	54	85	134,250	266,000	C & Serrated	365	6800	375	34	N.B.	...	
	23	3	...	...	...	...	...	...	810	oil	625	325	S	140,000	144,750	157,500	19.0	59.8	57.8	73	89	106,000	252,000	Star	320	5015	320	54	310	80,000	

TABLE 11 (Continued)

Group	Steel No.	Draw No.	Composition (Per Cent) C	Ni	Cr	Mo	V	Ce	Heat Treatment Quench °C.	Medium	Draw °C.	Tensile Data: Brinell Hardness	Prop. Lim. lbs./sq. in.	Yield Point Extensometer	Yield Point Drop Beam	Maximum Tensile Strength Orig. Area	Elong., % in 2″	Red. Area Neck %	Red. Area Fracture %	Merit Index^a	Elastic Ratio	Breaking Strength Orig. Area	Breaking Strength Red. Area	Nature of Fracture	Impact Data: Brinell Hardness Stanton Specimen	Stanton Blows to Fracture	Brinell Hardness Izod Specimen	Izod Test ft. lbs.	Endur. Data: Brinell Hardness Endurance Specimen	Endur. Limit Upton-Lewis test lbs. sq. in.^{b}	Remarks
E	22	A	.41	2.49	.79	.76	...	...	810	oil	150	530	170,000	187,500	N	312,000	11.2	29.6	26.5	40	60	279,000	380,000	C	N.B.	...	N.B.	...	530	135000 ±	
	22	X	...	...	...	...	...	...	810	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	530	22	475	125000 ±	
	22	B	...	...	...	...	...	...	805	oil	225	495	165,000	185,000	N	280,000	11.5	39.3	35.3	44	66	224,000	346,000	C	N.B.	...	N.B.	...	N.B.	...	
	22	C	...	...	...	...	...	...	805	oil	325	475	197,000	200,750	N	246,000	11.5	40.3	37.4	43	81	192,500	307,000	C	N.B.	...	N.B.	...	445	100000 ±	
	22	1	...	...	...	...	...	...	810	oil	425	445	S	175,000	180,000	220,000	12.0	40.3	37.0	40	80	174,750	277,000	C	(425)	6800	(425)	16	425	96,000	
	22	D	...	...	...	...	...	...	805	oil	425	420	190,000	195,000	N	223,000	12.2	40.4	37.0	43	87	172,000	273,000	C	N.B.	...	N.B.	...	N.B.	...	
	22	E	...	...	...	...	...	...	810	oil	475	420	165,000	172,500	N	203,000	13.2	43.1	38.6	44	85	150,500	246,000	C	N.B.	...	N.B.	...	N.B.	...	
	22	2	...	...	...	...	...	...	810	oil	525	410	S	165,500	170,000	204,250	14.5	45.0	41.2	49	81	157,250	268,000	C	(405)	5040	(405)	23	400	100,000	
	22	F	...	...	...	...	...	...	805	oil	550	410	162,500	170,000	183,500	198,500	15.0	46.0	43.1	52	86	154,000	271,000	C	N.B.	...	N.B.	...	N.B.	...	
	22	G	...	...	...	...	...	...	805	oil	540	400	165,000	175,000	180,000	200,000	15.5	48.0	46.5	56	87	149,500	279,000	C & Serrated	N.B.	...	N.B.	...	330	84,000	Endurance bars drawn 850–875° 1 hr. slow cooled
	22	H	...	...	...	...	...	...	805	oil	625	365	150,000	155,000	175,000	181,000	17.0	52.0	51.0	60	86	131,000	267,000	Star	N.B.	...	N.B.	...	N.B.	...	
	22	I	...	...	...	...	...	...	805	oil	600	360	150,000	157,500	172,000	184,000	16.5	47.1	45.7	53	86	140,000	258,000	Star	N.B.	...	N.B.	...	N.B.	...	
	22	3	...	...	...	...	...	...	810	oil	625	340	S	145,000	150,750	169,000	16.7	54.5	53.9	58	86	119,750	264,000	Star	(330)	4635	(330)	32	310	83,000	
	22	J	...	...	...	...	...	...	810	oil	650	320	140,000	146,500	146,500	157,500	18.0	55.0	54.5	61	93	N.D.	...	Star	N.B.	...	N.B.	...	275	72,000	End. bars slow cooled
	22	K	...	...	...	...	...	...	810	oil	675	295	127,500	133,000	133,000	146,000	19.0	55.4	54.8	60	91	105,000	233,000	Star	N.B.	...	...	...	N.B.	...	
	22	L	...	...	...	...	...	...	810	oil	750	270	95,000	100,000	103,500	132,000	25.0	55.8	53.9	66	83	99,500	216,000	C	N.B.	...	...	...	N.B.	...	
	26	X	.50	2.39	.86	.75	...	...	790	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	555	15	N.B	...	
	26	1	...	...	...	...	...	...	790	oil	430	465	S	207,000	213,000^m	237,750	10.0	34.0	31.4	34	87	195,750	285,000	C	460	4880	(460)	15	445	102,000	
	26	2	...	...	...	...	...	...	790	oil	525	425	S	190,000	193,500^m	209,750	11.5	37.2	36.3	37	90	173,000	272,000	C	430	4850	(425)	18	420	87,000	
	26	3	...	...	...	...	...	...	790	oil	630	335	S	150,000	154,750	163,750	16.0	49.1	47.3	50	91	126,500	240,000	C & Serrated	350	5540	(340)	34	320	70,000	
	24	X	.40	2.52	.84	...	.20	...	810	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	510	22	N.B.	...	
	24	1	...	...	...	...	...	...	810	oil	425	405	S	187,500	200,000^m	207,500	12.5	51.9	49.1	51	90	144,000	283,000	C & Serrated	415	8560	390	35	420	100,000	Izod varies—22 to 40
	24	2	...	...	...	...	...	...	810	oil	525	345	S	155,000	158,500	170,000	16.5	54.5	52.2	59	91	117,000	245,000	C oblique silky	350	5350	320	35	N.B.	...	Izod varies—28 to 42
	24	3	...	...	...	...	...	...	810	oil	625	320	S	140,000	150,000	152,000	17.0	54.5	53.0	55	92	104,500	223,000	C & Star irregular	300	4540	(300)	50	...	...	Tensile fracture much like that of steel 57 draw 3, Group C1
	25	X	.43	2.47	.95	...	...	.24	810	oil	225	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	N.B.	...	510	17	N.B.	...	
	25	1	...	...	...	...	...	...	810	oil	430	420	190,000	192,500	193,750^m	207,500	13.2	43.3	42.9	47	92	154,750	279,000	C	420	6900	(420)	17.5	N.B.	...	

E	25	2	...	...	...	...	...	...	810 oil	525	320	137,500	142,500	143,000	153,500	17.0	51.9	50.5	52	93	114,250	231,000	C & Serrated	330	4150	340	31	320	77,000	
	25	3	...	...	...	...	...	...	810 oil	630	265	105,000	115,000	124,000	127,250	23.0	56.7	56.1	65	90	92,250	210,000	C & Serrated	295	2600	320	47	N.B.	...	
F	53	F[n]	.31	...	...	...	...	.15	...	...	165	N.D.	N.D.	52,000	81,000	25.0	51.9	50.2	...	...	67,500	136,000	C	N.B.	...	N.B.	...	N.B.	...	0.07% Mn
	53	1	...	...	...	...	...	...	870 W	360	275	N.D.	N.D.	120,000	140,000	19.5	62.3	56.5	...	...	88,500	203,000	C	275	2860	(270)	67	...	...	Izod varies 58–68
	53	2	...	...	...	...	...	...	870 W	420	250	95,000	100,000	111,500	129,500	19.0	62.3	54.9	58	77	89,250	198,000	C	255	3000	255	70	...	...	Izod varies 62–73
	53	N	...	...	...	...	...	...	875 air	...	N.B.	...	...	...	...	...	...	...	...	...	...	...	...	135	770	135	61	...	...	Izod varies 53–78
	54	F[n]	.30	...	...	...	...	.05	...	...	165	S	64,000	68,500	88,750	19.0	57.3	55.5	34	72	64,250	144,500	C	N.B.	...	N.B.	...	N.B.	...	0.06% Mn–0.032% S
	54	1	...	...	...	...	...	...	870 W	360	200	N.D	N.D.	84,250	104,500	25.5	64.7	59.1	...	...	73,500	180,000	C	190	1800	190	90	...	...	
	54	2	...	...	...	...	...	...	870 W	420	195	N.D.	N.D.	83,125	103,750	23.5	67.0	61.6	...	...	70,500	183,000	C	190	2050	190	87	...	...	
	54	N	...	...	...	...	...	...	875 air	...	150	S	55,000	59,000	78,000	32.0	54.5	52.5	47	71	62,000	130,500	C	140	895	130	67	...	...	Izod varies 58–80

[a] See page 111 and Ref. 148.
[b] Stress given for Endurance Limit is half the stress range, i.e., either tension or compression.
[c] S= "Scissors" extensometer used—Prop. Limit not determined
[d] N= drop of beam noted.
[e] C= Cupped fracture, part cup and cone.
[f] Brinell figures in parentheses not directly determined, averaged from results on other bars
[g] N. B.= no bars tested.
[h] N. D.= not determined.
[i] U= Unnecked endurance bars only tested.
[j] No endurance plots—data lost in a fire in the Cornell laboratory.
[k] Bars cooled in furnace with door open, i e., between normalizing and annealing.
[l] Indeterminate because of nature of fracture.
[m] Drop of beam not well defined.
[n] F = as forged. Nos. 53, 54 forged, not rolled
[o] Two tensile bars, both broke with similar fractures. Bars split lengthwise at fracture, half of fracture at each end of the split. Split 0.6″ long. One half of fracture away from necked-down portion. Star fracture, but jagged and irregular.

ties are plotted against draw temperatures. Higher draw temperatures were used on molybdenum steels Nos. 2, 7 and 8 than on the carbon steels Nos. 1 and 6 in order to compensate to some degree for the hardening effect of the molybdenum.

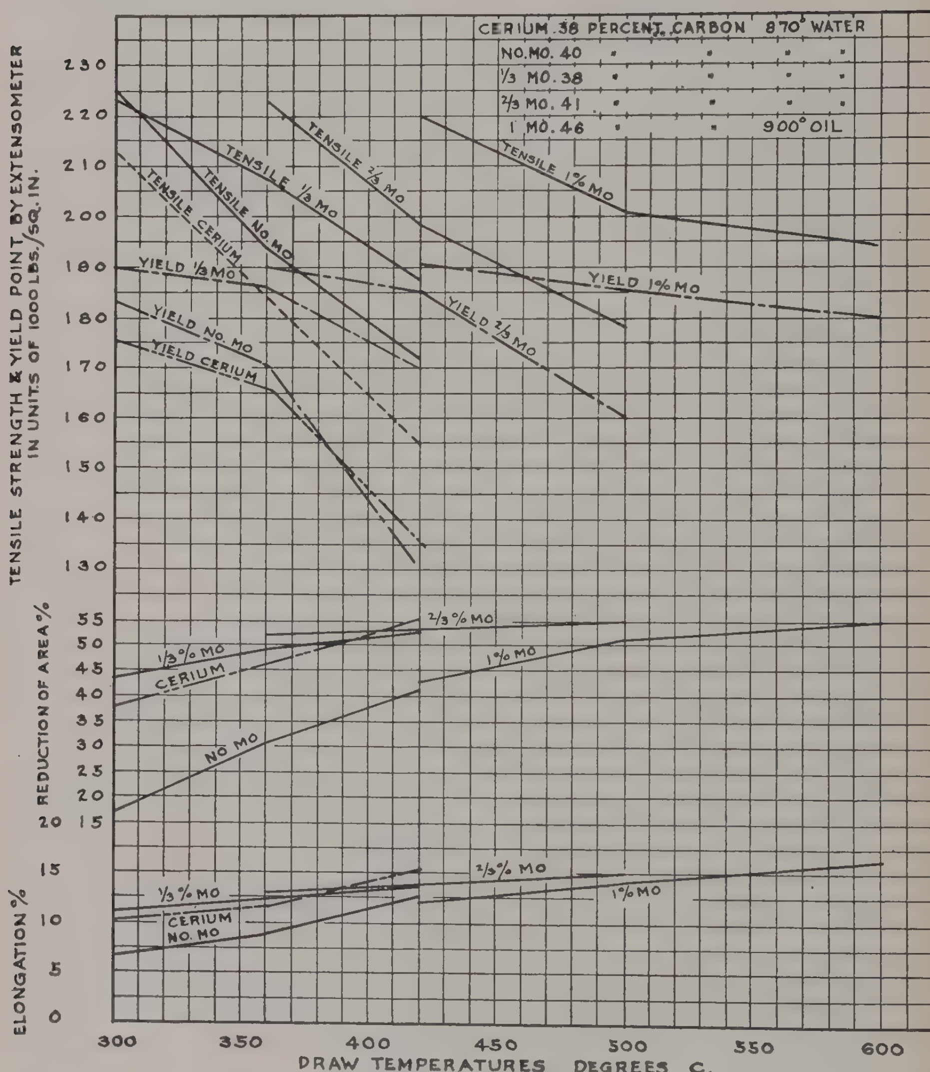


FIG. 24a.—Tensile properties of C-Mo steels.

A comparison of Groups A_1, A_2, and B is shown in Figs. 25 and 26. The curves show clearly the strengthening effect of molybdenum and bring out the fact that a given strength and hardness is obtained at a

higher draw temperature than in a plain carbon steel; and that for a given strength, the ductility of the molybdenum steel is greater. For example, at 170,000 pounds yield point and a tensile strength of about 190,000 pounds, the water-quenched molybdenum steels, instead of the 9 per cent.

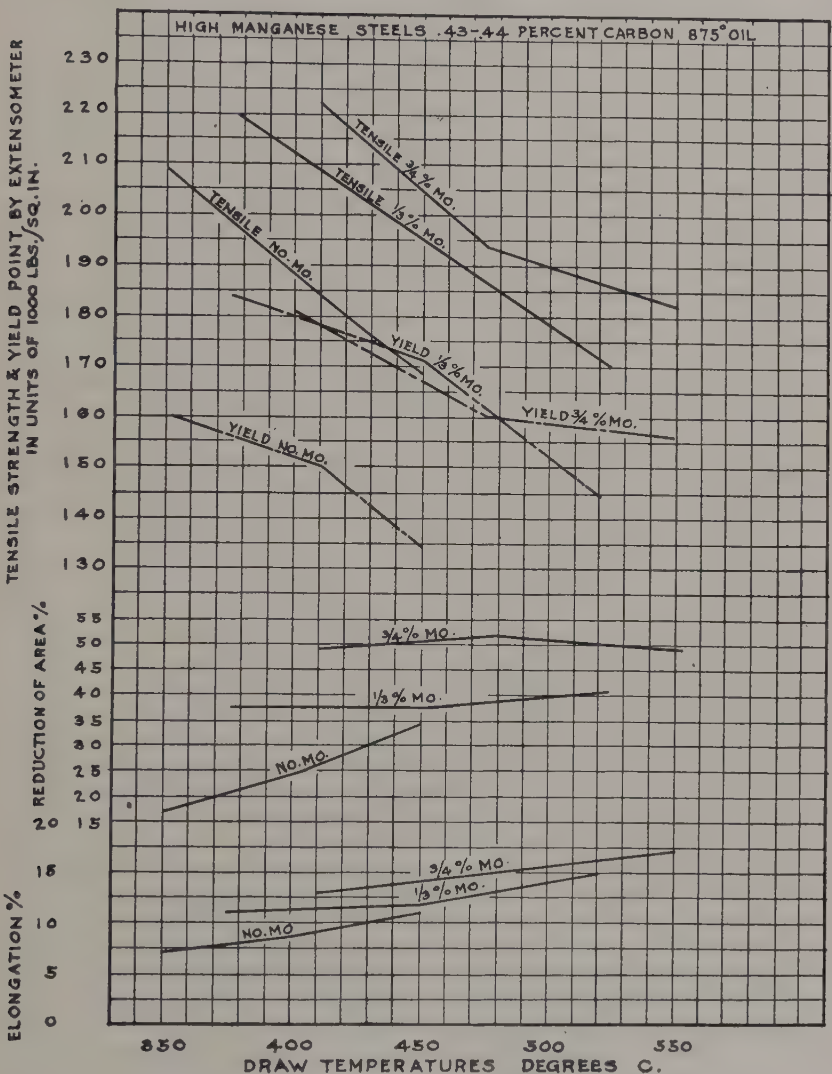


FIG. 24b.—Tensile properties of Mn-Mo steels.

elongation and 31 per cent. reduction of area of the carbon steel, give about 14 per cent. elongation and 52 per cent. reduction.

At 160,000 pounds yield point the oil-quenched molybdenum-manga-

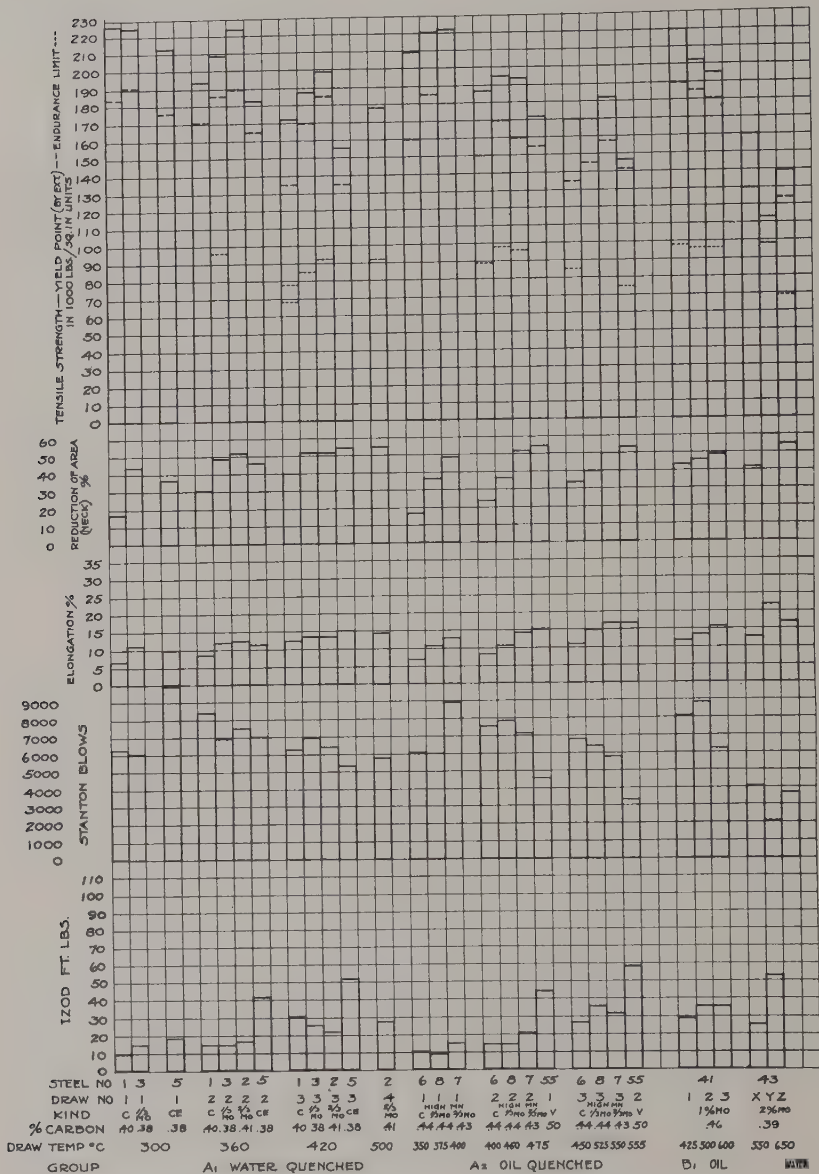


FIG. 25.—Comparisons of Mo, Ce, V and Mn-Mo steels.

nese steels, instead of the 7 per cent. elongation and 17 per cent. reduction of area of the manganese steel without molybdenum, give 14 per cent. and 52 per cent. respectively.

The merit index figures, approximately expressing the work done to fracture, are about doubled in these cases by the use of molybdenum. The cerium steel (No. 5) on the other hand, being slightly lower in carbon and manganese is weaker and more ductile than plain carbon steel No. 1, so that its merit index is somewhat higher, but there appears to be no strengthening due to cerium.

The only carbon-vanadium composition available for comparison is No. 55, (0.50 per cent. C, 0.20 per cent. V) oil-quenched, which is decidedly higher in carbon than the other steels under discussion. The difference in carbon and manganese content of the steels being compared makes accurate comparison of molybdenum and vanadium impossible in this series.

The steels considered above running to about 0.70 per cent. molybdenum are of the types of plain molybdenum steel that would most probably be used commercially, since steels containing over 1 per cent. molybdenum are seldom used.

The normalized specimens in this group will be considered in the general discussion of normalized molybdenum steels.

Group B

Steels of 1 to 3 per cent. Molybdenum—Nos. 39, 40, 41, 42, 43, 44

The results on steels of higher molybdenum content (Table 11, Group B) show that increasing the molybdenum content up to 2 per cent. in a 0.40 per cent. carbon steel increases the resistance to tempering. Such a steel, oil-quenched and drawn at 600° C. (1110° F.) has a Brinell hardness of 420. (See Fig. 27.) When the steel does begin to soften the hardness drops off rapidly with increase in draw temperature, as Fig. 27 shows. The same effect is shown by the addition of molybdenum to chromium-nickel steel. The persistence of hardness seems to be less marked in the 3 per cent. than in the 2 per cent. molybdenum steel.

When these steels of high molybdenum content are heat-treated to a given yield point, there appears to be little difference in ductility from that obtained with a lower molybdenum content. However, the Izod values for steel No. 41 (1.05 per cent. molybdenum are higher for a given Brinell hardness than with lower molybdenum content and the Stanton figures are about the same. On No. 43 (1.90 per cent. molybdenum, quenched from a lower temperature than the other steels) the Izod values are lower.

Steel No. 42 (2.05 per cent. molybdenum) gives very good Izod values

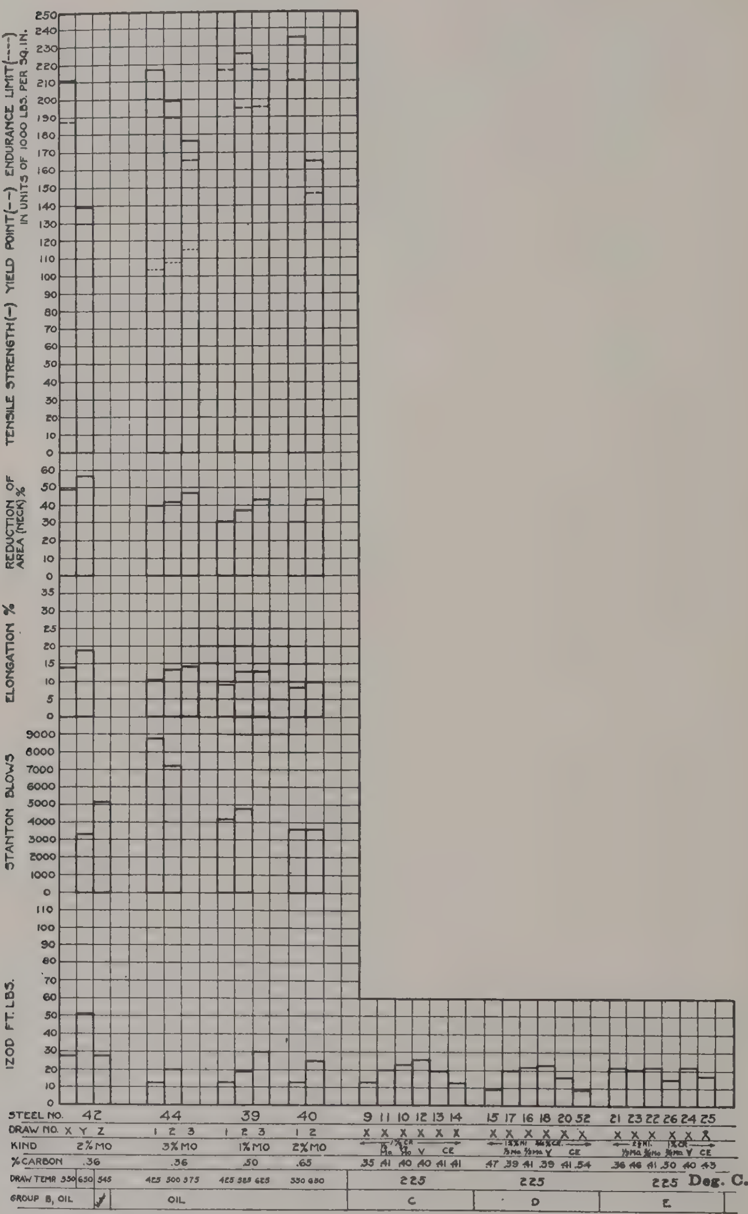


FIG. 26.—Properties of some high molybdenum steels and impact data on the steels of Fig. 25 at a low draw temperature.

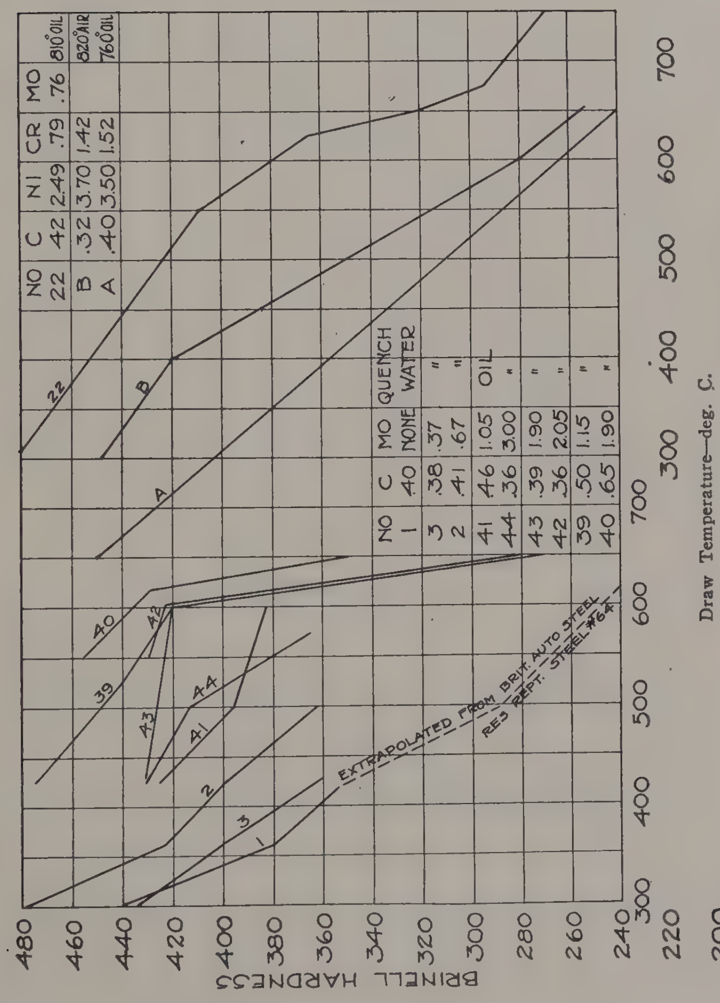


FIG. 27.—Change in Brinell hardness of Mo steels with increase in draw temperature.

(27 and 28 foot pounds) on specimens of about 425 Brinell hardness drawn at 550° C. (1020° F.), while steel No. 44 (3.00 per cent. molybdenum) gives a value at 425 Brinell hardness obtained by drawing at 425° C. (800° F.) about the same (12.5 foot pounds) as on a carbon steel of the same hardness. At practically the same Brinell hardness on specimens drawn at 500° C. (930° F.) the Izod value is raised to 20 foot pounds. Of the high carbon steels, No. 39, with 0.50 per cent. C, 1.15 per cent. Mo, also gives high Izod values, showing 29.5 foot pounds at 420 Brinell hardness, on specimens drawn at 625° C. (1150° F.) No. 40, with 0.65 per cent. C, 1.90 per cent. Mo, gives Izod values no higher than the 0.40 per cent. carbon steels of under 1 per cent. molybdenum, probably because of the effect of the high carbon content.

There is some indication from this data that the higher tempering temperature possible on steels high in molybdenum tends to give higher Izod tests for a given hardness and given tensile properties accompanying that hardness. While the tendency in the commercial use of molybdenum in plain carbon steels is toward a molybdenum content of certainly not over 0.50 per cent. because the tensile properties are not improved in the same ratio by further increments, it is possible that for purposes where high hardness and high Izod tests are required, steels of higher molybdenum content might be useful.

Groups C_1 and C_2, Heat-treated

Steels Nos. 9, 11, 12, 13, 14, 16, 27, 28, 29, 30, 45, 57: 46, 47, 48, 49, 50

Groups C_1 and C_2 (Table 11 and Fig. 28) include the most interesting of the steels studied, the chromium-molybdenum steels of commercial compositions.

They afford a comparison among chromium-molybdenum steels of different carbon content and among chromium, chromium-molybdenum, chromium-vanadium and chromium-cerium steels of approximately the same carbon content.

The two steels below 0.25 per cent. carbon were water-quenched, the rest oil-quenched, quenching temperatures being varied according to carbon content.

All the steels were drawn at the same temperatures, 425°, 525°, and 625° C. (800°, 975°, 1155° F.), except in the case of the plates (steels Nos. 27, 28, 29, 30) (Tables 12 and Fig. 51), Chapter 10, which were drawn at 550° C. (1020° F.).

Steel No. 10, with 0.68 per cent. molybdenum is seen to have the highest tensile strength at all draws of any of the 0.40 per cent. carbon steels of its group, its strength at the highest draw temperature again

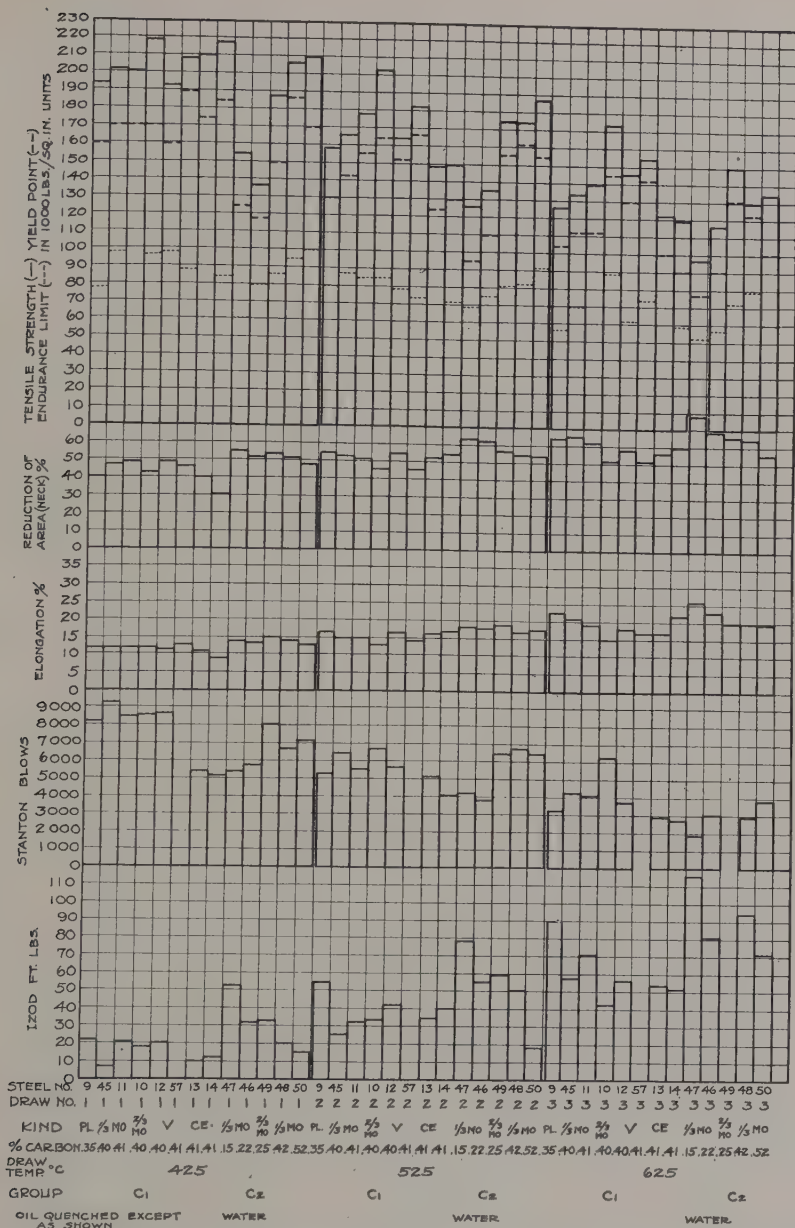


FIG. 28.—Properties of Cr, Cr-Mo, Cr-V and Cr-Ce steels. Cr content 0.88-0.98 per cent., except No. 47, 0.73 per cent.; No. 46, 0.79 per cent. and No. 48, 0.55 per cent.

showing the resistance to tempering conferred by molybdenum. The elastic ratio of the chromium-vanadium steels is in some cases a trifle higher than that of the other steels. For a given strength, the ductility of the plain chromium steel runs below that of the others, and the ductility of the cerium steel, especially at the lowest, draw, is also inferior. The chromium-molybdenum and chromium-vanadium steels of similar carbon content act about alike in their relationship between strength and ductility.

The discussion of the specimens cut from plates in Group C will be taken up in connection with similar specimens from plates in Group E.

Steels Nos. 15, 16, 17, 18, 20, 21, 22, 23, 24, 25, 26, 52
Groups D and E

To study the effect of molybdenum and cerium as added alloying elements in chromium-nickel steels, two other groups of steels were studied, Group D with about 0.40 per cent. C, 1.25 per cent. Ni, 0.70 per cent. Cr, and Group E with about 0.40 per cent. C, 2.50 per cent. Ni, 0.90 per cent. Cr.

Each steel was oil-quenched from a temperature chosen according to its composition, and (except the plates of Group E) each was given three draws at the same temperatures. The data are plotted in Fig. 29.

The ductility of the steels containing cerium consistently falls below that of the other steels, for a given tensile strength, and without any corresponding increase in strength. Cerium Steels Nos. 20 and 52 showed some longitudinal seams.

The introduction of molybdenum brings the same result that it has shown in previous series, *i.e.,* it markedly increases the strength and hardness at a given draw temperature. The introduction of vanadium has a similar but weaker effect, it being noticeable only at the highest draw temperatures used. With vanadium the ductility is reduced proportionately to the increase in strength, while with molybdenum the ductility appears to be cut down to a lesser degree.

However, on account of the difference due to the greater strength of the molybdenum steels at a given heat-treatment, comparison of ductility on these steels is difficult. It is easier in the case of the longitudinal specimens from plates of Group E, Steels Nos. 32, 33, 34, 35, 36, (Fig. 51, Chapter 10) which were drawn to approximately the same Brinell hardness, and have about the same carbon content. In this case the elongation is slightly increased and the reduction of area unchanged from that of the chromium-nickel steel, while with vanadium there is a very slight increase in elongation and a small decrease in reduction. Cerium again decreases the ductility.

The draw temperatures required to produce the same hardness on

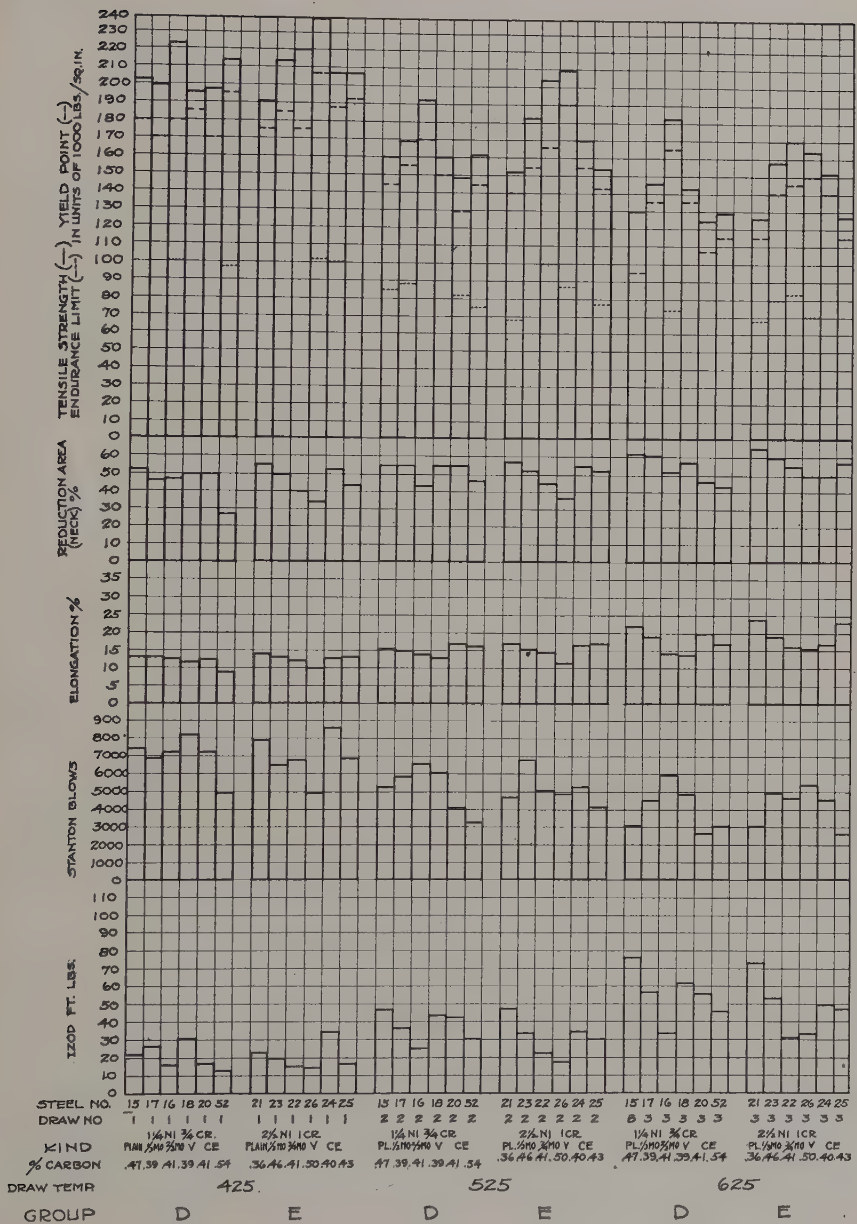


FIG. 29.—Properties of Ni-Cr-Mo, Ni-Cr-V and Ni-Cr-Ce steels.

these plates indicate, as do the tensile results, that 0.20 per cent. vanadium acts as a hardener and strengthener in the chrome-nickel steels but not to as great a degree as 0.35 per cent. molybdenum. The elastic ratio of the vanadium steels averages a trifle higher than that of the others.

Impact Tests

In studying the Stanton and Izod impact tests it is obvious that comparisons of heat-treated steels must be made by inter-comparison with some other property. The Brinell hardness appears to be a suitable basis for comparison. When all the Stanton and Izod data are plotted against Brinell hardness as in Figs. 30 and 31, it is seen that the points fall about curves of the same general shape as were shown in Figs. 1 and 23 as characteristic for these tests. Inasmuch as the maxima or minima of the curves are probably located at somewhat different Brinell hardness values for different steels, such a comparison is necessarily a very rough one. These impact tests are tests to destruction and the energy to rupture a high carbon steel and a low carbon steel of the same Brinell hardness, but with different ductilities, will be different.

The highest Stanton value is that for steel No. 5, draw 1, as plain carbon-cerium steel, but the other draws of this steel do not give high values.

Steel No. 45, draw 1, a chromium-molybdenum steel, gives the next highest Stanton value, but the corresponding Izod test is the lowest of any of the heat-treated steels. Steel No. 7, draw 1 (high-manganese-molybdenum), and No. 16, draw 1, a nickel-chromium-molybdenum steel, both show high Stanton values. Each is found to be high in either strength or ductility, in comparison with other steels of its class, on tensile test.

Among the steels obviously low in Stanton values are three of the highest carbon steels tested, No. 40, draw 1 (0.65 per cent. C, 1.90 per cent. Mo.); No. 26, draw 2 (0.50 per cent. C, 2.39 per cent. Ni, 086 per cent. Cr, 0.75 per cent. Mo); and No. 55, draw 1 (0.50 per cent. C, 0.20 per cent. V).

Another of the high molybdenum steels, No. 42, draw 2, (0.36 per cent. C 2.05 per cent. Mo); one chromium-molybdenum, No. 28 (plate) (0.42 per cent. C, 0.93 per cent. Cr, 0.73 per cent. Mo); and one nickel-chromium-molybdenum, No. 22, draw 2, (0.41 per cent. C, 2.49 per cent. Ni, 0.79 per cent. Cr, 0.76 per cent. Mo) are on the low side. Most of the cerium steels fall below the curves, although a few give as high values as any of the steels.

But among the steels without molybdenum or vanadium, and among those containing these elements, the points show about the same deviation from the curve. It seems obvious that any differences in resistance to repeated impact in notched-bar form are due to other causes than to

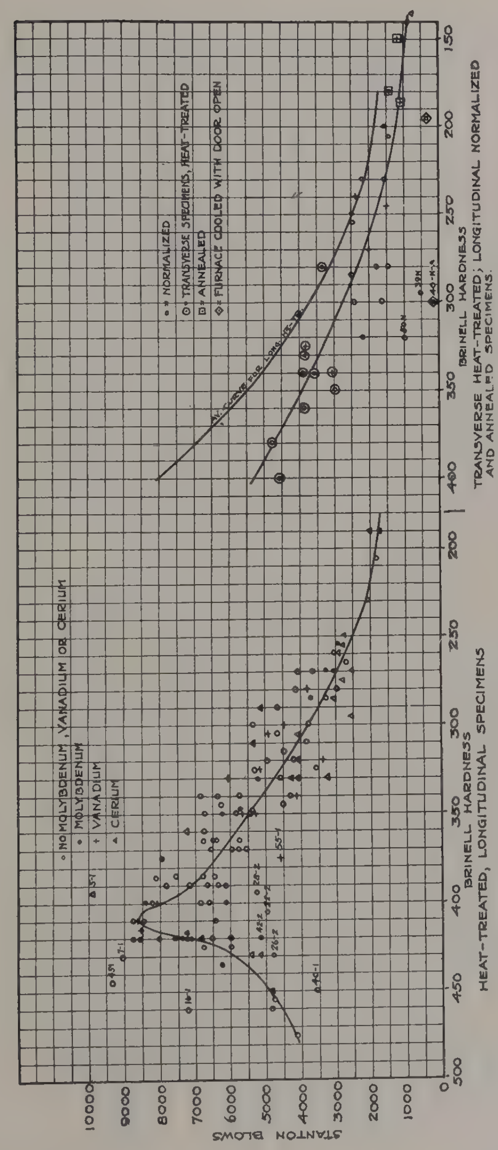


FIG. 30.—Stanton repeated-impact tests plotted against Brinell hardness.

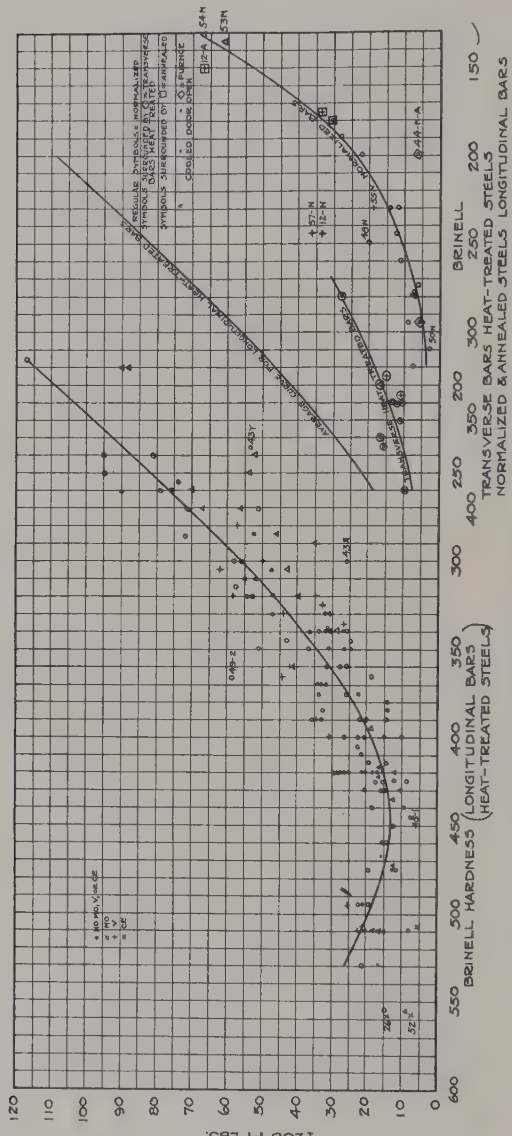


FIG. 31.—Izod single-blow impact tests plotted against Brinell hardness.

chemical composition. There is no consistent difference in a given class of steel of a given Brinell hardness whether molybdenum or vanadium is present or not.

In considering the Izod tests (Fig. 31) we find a similar state of affairs. The greatest deviation from the average at very high hardness is shown by steels No. 26, draw X, and No. 52, draw X, both high in carbon, while steel No. 15, draw X, is also on the high side in carbon content. These "X" draws (Fig. 26) were made for Izod tests only, because in another investigation on alloy steels in which some compositions containing cerium were tested, two of the cerium steels showed relatively high Izod values at low draw temperatures and it was desired to determine whether that behavior could be duplicated in these steels. As Fig. 26 shows, the steels containing cerium showed no superiority.

Steel No. 43, draws X and Y (0.39 per cent. C, 1.90 per cent. Mo) both of which were oil-quenched from a much lower temperature than other specimens, give low Izod values.

One steel, No. 49 (0.25 per cent. C, 0.95 per cent. Cr, 0.72 per cent. Mo), at draw 2, shows a very high Izod value and the other two draws also give values on the high side.

The steels containing cerium, as a rule though not invariably, give Izod values that fall below the curve, so that in the single-blow impact test as in the repeated-blow tests, cerium appears to have a detrimental effect. This is probably due to the inclusions present in great numbers in these steels.

The steels containing neither molybdenum nor vanadium, and those containing these elements, give points uniformly distributed about the curve and, as was the case with the Stanton tests, we must look to other causes than the presence or absence of these elements for high or low Izod values.

The Stanton and Izod test results on transverse specimens from heat-treated steels and on normalized or annealed specimens will be discussed in Chapter 9.

Chapter 8.

Endurance Tests of Heat-Treated Molybdenum and Cerium Steels.

In considering the graphic representation of the endurance test results, the conventions used in plotting should be kept in mind. The stress plotted is the half-stress range, *i.e.*, the (equal) tensile or compressive stress. Stress (S) is plotted on ordinary, and number of cycles (N) on logarithmic, scaling. An arrow attached to a point indicates that the specimen was unbroken at that stress. Converging lines are drawn connecting points for specimens unbroken at a low initial stress, and those for the same specimen re-tested at higher stresses. Because of the strengthening effect of understressing, the points at raised stresses are not used in plotting the curve; they serve merely to verify the assumption that the specimen has been undamaged at the lower stress and that it would probably last much longer at the lower stress without fracture. A diagonal line through a point indicates that the specimen broke above or below the point of minimum section. The points usually show considerable "scatter," and the curves drawn are idealized, when too few points are available to actually determine the course of the curve. The curve is drawn as an average, hence points denoting fracture may be found below this curve if they are balanced by other points above the curve.

Had the object of the work been to determine the limit of reliability of any particular lot of steel, it would have been necessary to draw a curve of the ideal shape through the lowest of the scattered points but, since the object was the comparison of the inherent properties of different classes of steels, it appears better to make such a comparison on average rather than minimum, values.

Not every steel was tested for endurance at every draw, nor were more specimens tested than were essential to fix the endurance limit with a reasonable degree of accuracy, because of the time consumed by endurance tests. The idea was to test many different steels rather than to test any one steel exhaustively. For a complete study of any one steel many other variations in heat-treatment and many more different draws would be required. Most of the available stock on some steels was used

in fruitless testing of un-necked specimens leaving a scanty supply or none at all for the preparation of necked specimens.

The endurance limit is taken as the highest stress at which a specimen will withstand one million stress cycles. This may be a trifle higher than would be the case were 10 million cycles taken as the criterion, but this is balanced by the fact that the test-pieces necked-down with a 1 inch radius have, according to Moore, true stresses 1 or 2 per cent. above the calculated values.

The extrapolation of the ideal curve to 10 million cycles is arbitrarily drawn slightly sloping to represent the authors' idea of the behavior of actual steels, without denying that with a perfectly clean, homogeneous steel and perfect surface finish, the curve would finally become parallel to the stress axis.

In studying the endurance test results to determine whether molybdenum aids, injures, or is without effect upon the endurance properties, it is necessary to select some general basis for comparison.

As is stated in Appendix B, Moore, McAdam and various English investigators find that the endurance limit is equal to 45 to 55 per cent of the tensile strength. Moore draws straight-line plots showing relations between tensile strength and endurance, and between Brinell hardness and endurance. Such a relationship seems well adapted as a basis for comparison. But on examining Moore's data we find that account was not taken in plotting his tensile strength *vs.* endurance graph, of two points for very hard steels (nickel steel draws AA and BB) given in his table (172, p. 31), on which endurance limits were estimated from a small number of specimens. If these points are included in Moore's diagram it is found that they are outside the normal deviation, and if the graph be drawn to give these points weight, the upper end of the curve is not a straight line, but curves off at about 175,000 to 200,000 pounds tensile strength so that at 280,000 tensile strength the endurance limit is about 118,000 pounds instead of 140,000 pounds, as indicated by the uncorrected curve. Although the two points referred to do not appear on Moore's yield point-endurance curve, yet at yields above 120,000 pounds that curve also deviates from the straight line. Moore states that the Brinell hardness-endurance limit straight-line relation holds up to the point (about 400 Brinell hardness) where the Brinell test is unsatisfactory on account of deformation of the ball. But from the shape of the tensile strength-endurance and yield point-endurance curves it seems that the Brinell hardness-endurance curve should be of a similar shape.

Data from Aitchison (184) on very hard chrome-nickel steels also indicate that the graph should be a curve rather than a straight line.

In Fig. 32, data from Moore, McAdam and Aitchison as well as the data of the authors, have been plotted together.

Many of the individual S-N curves are given in separate figures, but quite a number are omitted in order to conserve space. Fig. 32 includes only longitudinal specimens, and of the authors' tests on heat-treated steels, only those with a single one-hour draw. The results on the molybdenum and the vanadium and other steels used for comparison generally agree well with those of the other observers on other steels.

Obviously there is no great difference in the endurance properties of molybdenum steels (including chrome-molybdenum and nickel-chrome-molybdenum) and those of other alloy steels when the tests are confined to forged or rolled material, and to specimens stressed in the direction of working (longitudinal specimens), as long as the endurance is compared on the basis of tensile strength or Brinell hardness.

Lessels (264) has given endurance limits of a carbon steel and of another steel of practically identical composition except for the presence of 0.18 per cent. vanadium. His tests were on cast steel, tested in the as-cast, annealed, and normalized states. The endurance limits were determined both on rotating beam and cantilever specimens and average, for the carbon steel 42 to 46 per cent. of the tensile strength, and for the vanadium steel 48 to 54 per cent. If Lessels' figures are plotted on Fig. 32, they vary from the curve no more than do the other plotted test results.

Cast steel may offer a different problem from the wrought steels of Fig. 32, and the finer grain of a vanadium steel should tend toward better endurance, but in view of the fact that wrought carbon steels usually have an endurance limit of 45 to 55 per cent. of the tensile strength, which is all the vanadium steel gave, even this direct comparison leaves the subject open.

There is considerable evidence, however, that alloy steel as a class is rather more likely to give results falling on or above the curve of Fig. 32 while carbon steel is rather more likely to give results falling on or below it. Differentiation among the common alloy steels as to endurance properties does not seem justified on the basis of evidence so far at hand.

A differentiation, however, must be made in the case of the cerium steels.

Cerium steels, represented by triangles in Fig. 32, generally fall below the average line, rather than above it, which is doubtless due to the fact that cerium steels as a class are dirty, containing many non-metallic inclusions. The difference is, however, scarcely as much as would be expected from the dirtiness of the cerium steel.

A few results were lower than would be expected, from the average curve. These are steel No. 1, draw 3; steel No. 9, draw 1; steel No. 14, draw 1; steel No. 16, draw 3; steel No. 47, draw 1; and steel No. 57, draw 2. Of these the first two are steels drawn at the relatively low temperature of about 425° C. (800° F.). It will be shown later that at

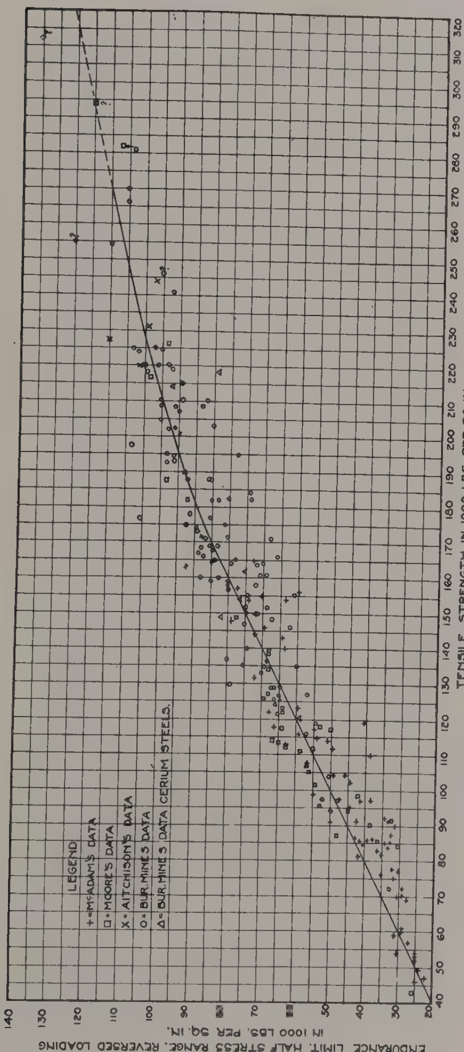


FIG. 32.—Relation between endurance limit and tensile strength of steels.

low drawing temperatures low and irregular results may be obtained, probably due to incomplete release of internal quenching stress.

Examining these low results individually, it is seen (Fig. 33) that specimen No. 1-3, plain carbon steel, gave erratic results, one piece tested at 74,000 pounds per square inch being unbroken after about 1,400,000 cycles, and withstanding 400,000 cycles when the stress was raised to 80,000 pounds per square inch. Another specimen broke after 260,000 cycles at 68,000 pounds per square inch, the better specimens indicating an endurance limit well within the normal range, while the poorer one indicates one below it.

Another set of endurance specimens of No. 1-4, Fig. 33, was then prepared and gave results indicating an endurance limit of 78,000 pounds per square inch.

The steel was found to be dirty. Plate 2a shows an unetched cross section of the specimen of draw No. 4, testing 1,740,000 cycles, unbroken, at 82,000 pounds per square inch and 96,000 cycles, broken, on raising the stress to 97,000 pounds per square inch. Plate 2b shows an unetched cross section of the specimen of draw No. 4 which broke at 80,000 cycles at 80,500 pounds per square inch stress. The structure of the latter is shown in Plate 2c.

The specimen which gave the lower result is the dirtier, but no great stress can be laid on this because, in order to polish the piece for metallographic examination, it is necessary to grind it flat so that the actual nucleus of fracture is lost and the evidence destroyed. In the early work on the un-necked test-pieces much time was spent in attempting to mount and polish specimens so that the actual nucleus could be examined, but always without success. The number of inclusions may vary greatly in localities only a few hundredths of an inch apart.

The specimens which, on examination of many sections, were uniformly dirty, generally showed a low endurance limit and gave erratic results. The behavior of a specimen under repeated stress in the Upton-Lewis test, using round test-pieces, appears to depend on the cleanliness or dirtiness of the steel at the exact point of maximum stress, and the deviations noted from the calculated value may depend very largely on the presence or absence of local "stress-raisers" at the critical section.

The breaking of a specimen at a point above or below the minimum section probably occurs when the steel is clean at the point of minimum section and dirty above or below this point.

Another factor which may enter with martensitic steels such as this, which was water-quenched and drawn at a relatively low temperature, is the presence of quenching stresses, not completely relieved by tempering.

Steel No. 9-1 (Fig. 34), a plain chromium steel, is also erratic, two specimens breaking at stresses that would indicate an endurance limit of

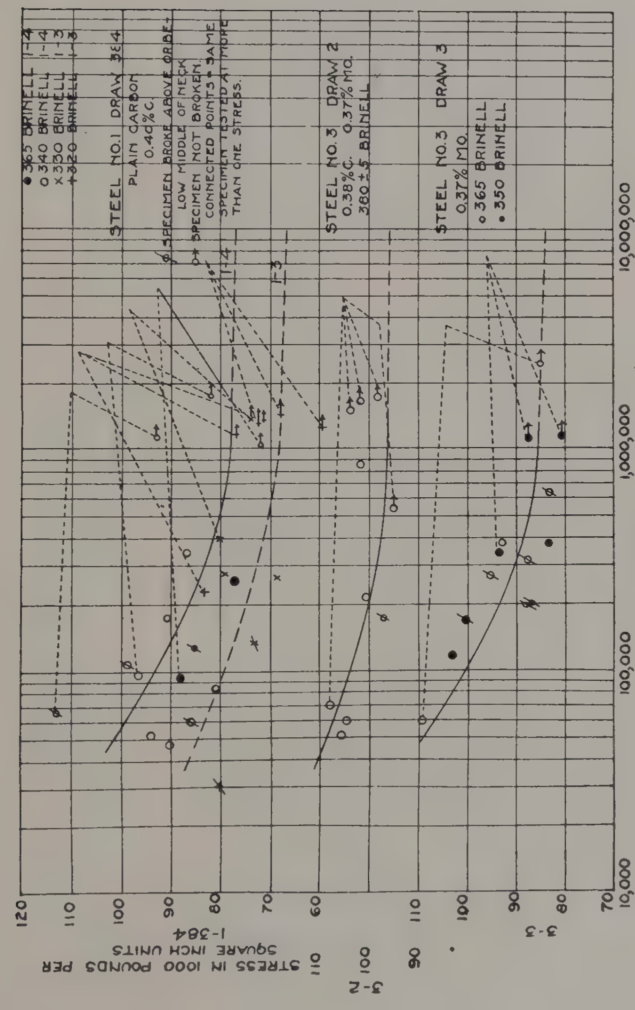
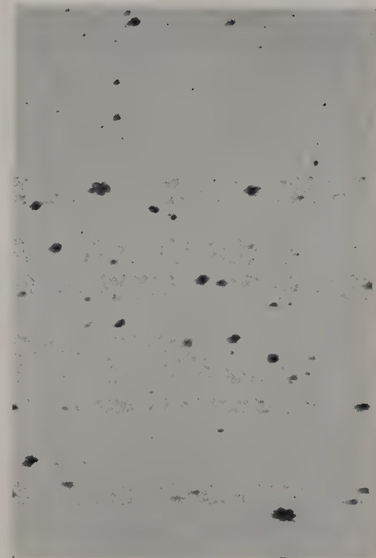


FIG. 33.—Endurance curves for carbon and molybdenum steels.

2a

Un-etched. × 100.

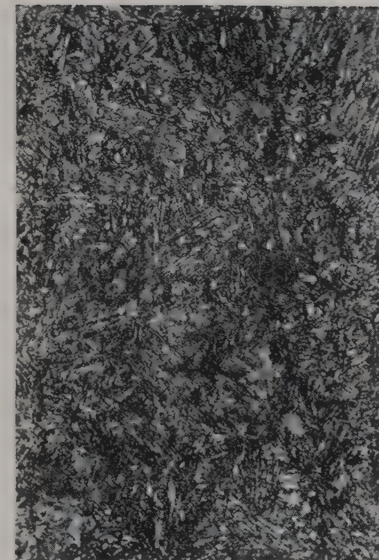
Endurance specimen 1-4-67-B. Section across direction of rolling. Stress 82,000 lbs./sq. in.; life, 1,740,000 cycles, not broken. Stress raised to 97,000 lbs./sq. in.; life, 96,000 cycles, broken.



2b

Un-etched. × 100.

Endurance specimen 1-4-61-B. Section across direction of rolling. Stress 80,500 lbs./sq. in.; life, 80,000 cycles, broken.



2c

Etchant: Alcoholic picric acid. × 500.

Endurance specimen 1-4-61-B.

PLATE 2.—Plain Carbon Steel No. 1; Draw No. 4.

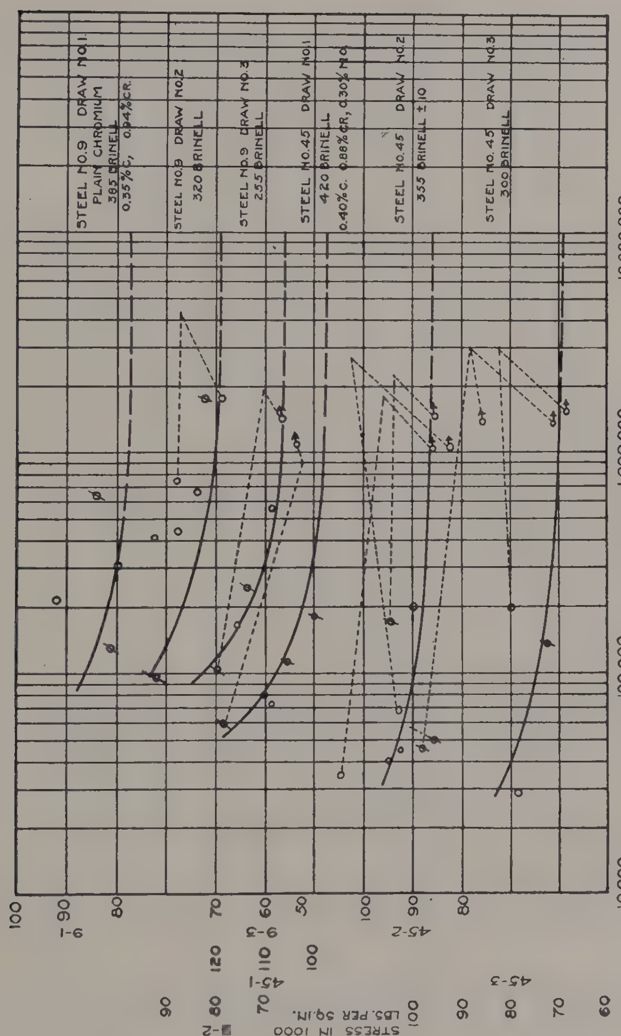


FIG. 34.—Endurance curves for chromium and chromium-molybdenum steels.

normal value, while two gave low values. No more stock was available on this steel for further testing.

No. 14-1 (Fig. 35) is a cerium steel and was decidedly dirty (Plate 3-a-b-c). No. 16-3, a nickel-chromium-molybdenum steel, (Fig. 36) gave concordant results indicating a low endurance limit. No. 47-1, a low chromium-molybdenum steel (Fig. 35) had all specimens breaking away from the point of minimum section, and too few specimens were available to determine the endurance limit accurately. No. 57-2 (Fig. 37) a chromium-vanadium steel, gave concordant results indicating a low endurance limit. Draw No. 1 on this same steel also gave slightly low results and almost all the specimens broke away from the middle of the neck. This steel showed a considerable variation in cleanliness (See Plate 8, p. 182.)

Steel No. 44, 0.36 per cent. C, 3.00 per cent. Mo, (Fig. 38) gave high results at the two higher draw temperatures.

This steel shows the characteristic property of molybdenum in requiring high draw temperatures to soften it (see Fig. 27) and the high results are probably due to the fact that temperatures sufficient to bring about very considerable release from quenching stresses still leave the steel very hard and strong.

The steel is not exceptionally clean. See Plate 4a. It is of interest to compare the plain carbon steel No. 1, draw No. 3 or 4, Plate 2, and this high molybdenum steel No. 44, draw 3, Plate 4. The Brinell hardness numbers are No. 1, draws 3 and 4, 325 to 350 on different specimens; and No. 44-3, 355 to 370. The tensile properties differ hardly at all, except for slightly better ductility on No. 44-3. Yet the stress for a life of a million cycles, unbroken, on No. 1 runs from 68,000 to 78,000 pounds per square inch with one specimen going up to 90,000 pounds, while No. 44-3 shows a stress for a life of one million cycles of 115,000 pounds per square inch, with one specimen going down to perhaps 100,000 pounds. The structures of the steels are, No. 1, martensitic, and No. 44, finely sorbitic. Plates 2c and 4b.

The draw temperatures were 420°-425° C. (800° F.) for No. 1 and 575° C. (1065° F.) for No. 44. No. 1 was water-quenched, No. 44 oil-quenched.

The martensitic structure alone does not mean that the endurance limit will be low. Plate 4c shows the structure of steel No. 50 (0.52 per cent. C, 0.95 per cent. Cr, 0.39 per cent. Mo), draw 1, (425° C.—800° F.) which at a Brinell hardness of 420-445 gives an endurance limit of 100,000 pounds per square inch, (Fig. 39) which is close to Moore's average curve. Nevertheless, it seems that the tensile strength-endurance limit relation begins to deviate from a straight line at about the point where martensitic structures begin to appear.

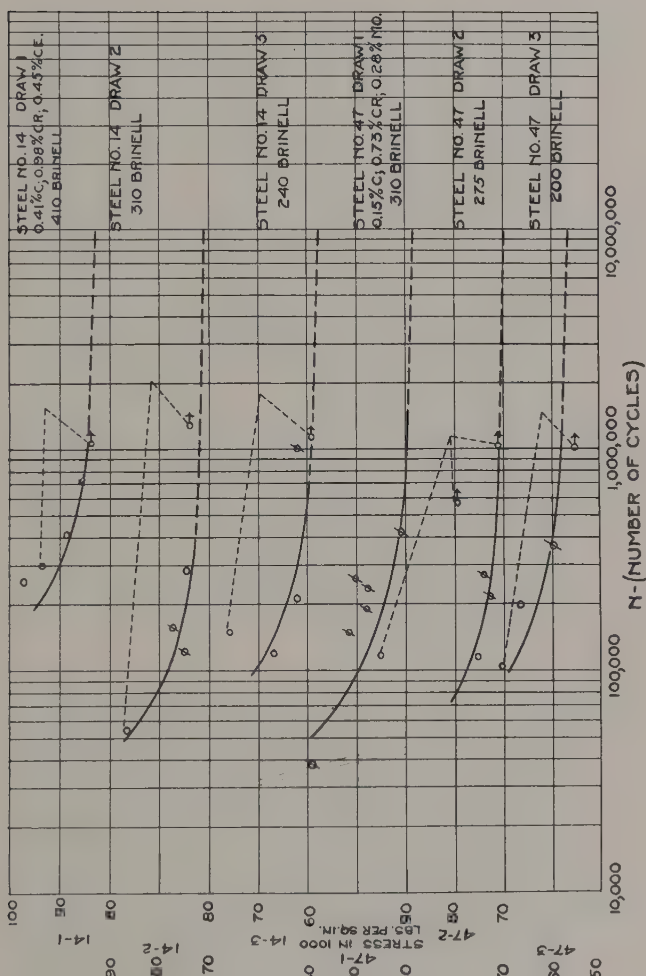


FIG. 35.—Endurance curves for Cr-Ce and Cr-Mo steels.

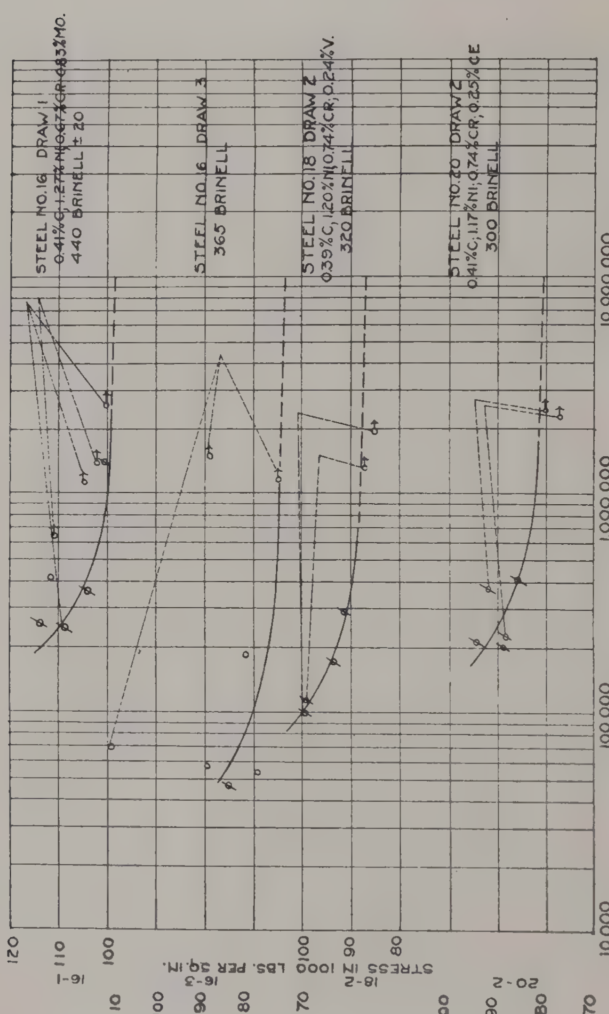


FIG. 36.—Endurance curves for Ni-Cr-Mo and Ni-Cr-Ce steels.

3a 3b 3c

All un-etched. × 100. All sections across direction of rolling.

PLATE 3.—Inclusions in three different endurance specimens of chromium-cerium steel No. 14; draw No. 1.

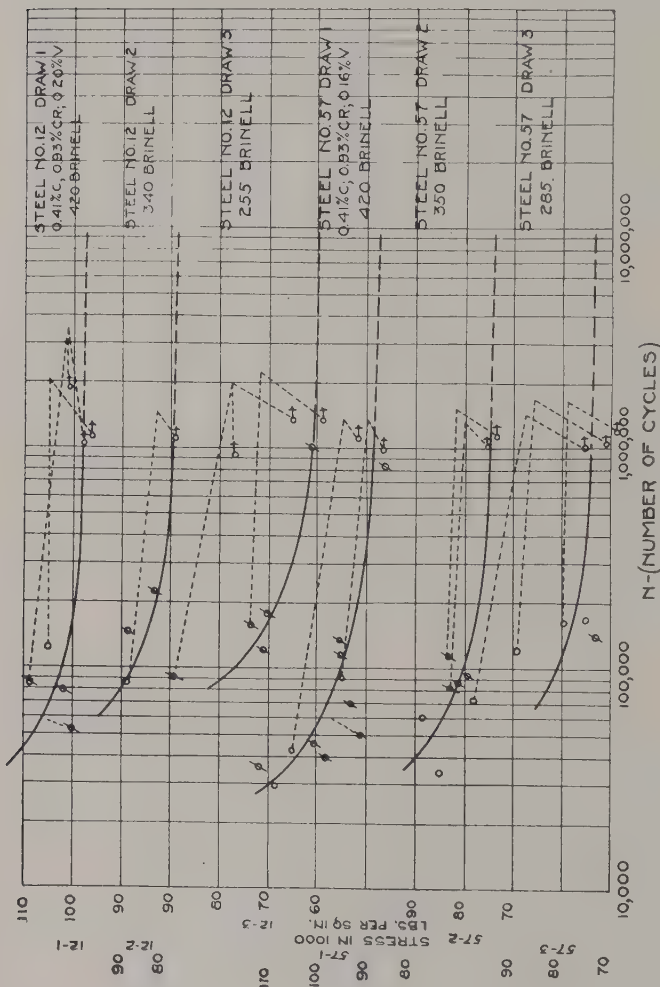


FIG. 37.—Endurance curves for chromium-vanadium steels.

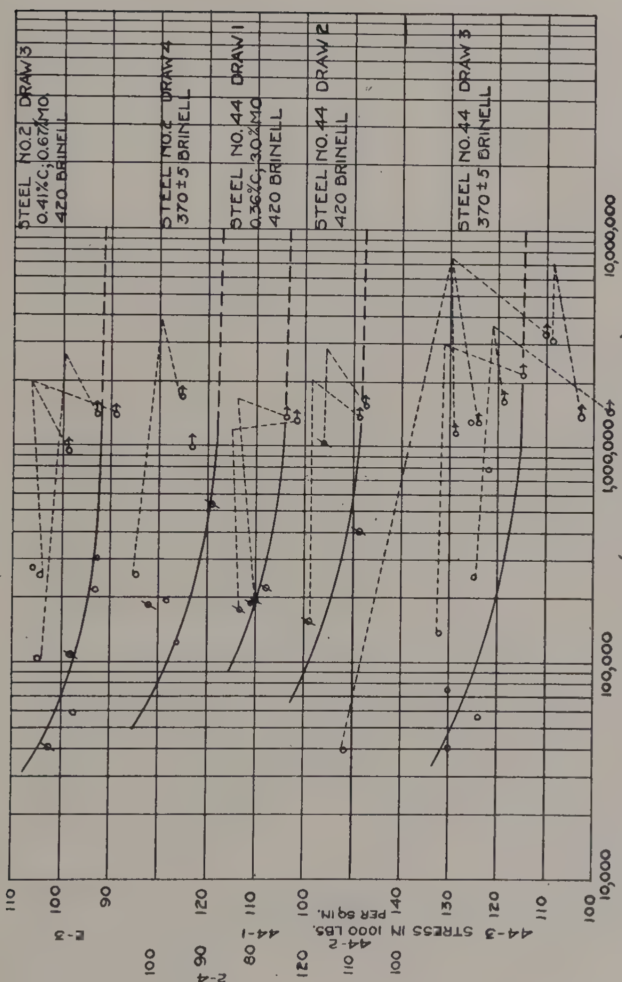


FIG. 38.—Endurance curves for carbon-molybdenum steels.

Steels Nos. 46-1 (Fig. 40) and No. 48-3 (Fig. 39) which also give rather high endurance results are chromium-molybdenum steels.

With the exceptions above noted, all the rest of the steels of whatever composition, group themselves as closely as could be expected about the average line of Fig. 32. Only one of the cerium steels No. 20-2, Fig. 36, (nickel-chromium-cerium), is above the average line, the great majority of the steels containing cerium giving results on the low side. In considering the individual S-N curve for the cerium steels, it is noted that they often show a marked "scatter" of the points (see steels No. 5, draws No. 2 and No. 3, Fig. 41; Steel No. 2, Draw 1 Fig. 42). Since these cerium steels are always dirty, (see Plate 8c, Chap. 9) one logical explanation is that the minute points of the necked Upton-Lewis bar which receive the maximum stress in the endurance test may or may not happen to lie at a dirty spot.

If we calculate the volume stressed to within 1½ per cent. of the maximum in a rotary-bending or reversed-bending test-piece and consider what this volume would be equivalent to as a tensile test-piece, we find that the volume so stressed in McAdam's tapered specimen for his rotary cantilever test is about the same as that of the exposed lead at the tip of an Eversharp pencil. In Moore's necked test-piece for the Farmer rotary bending test, the equivalent tensile specimen would go in the eye of a small sewing needle. In the round, necked, Upton-Lewis test-piece the highly stressed volume is so small that an equivalent tensile specimen would be of microscopic dimensions. The bending tests stress to the maximum only a small area of the surface of the test-piece. While inclusions are generally very small they are of real magnitude in comparison with the highly-stressed volume of a repeated-bending endurance test-specimen.

The results from steels containing molybdenum, those containing vanadium, and those containing neither, are shown by Fig. 32 to be so uniformly distributed about the average curve that, as in the case of Stanton and Izod tests, there appears to be nothing in the chemical composition itself to alter the relation between tensile strength and endurance limit. In fact in the softer steels, say through the machineable range, the one main factor affecting the endurance limit appears to be the strength of the steel. At a given tensile strength the chances that the endurance limit will be either on the high or low side of the average appear to be the same whether the steel be a plain carbon steel, a chromium or nickel-chromium steel, or any of these three with either vanadium or molybdenum.

That other factors do enter in is obvious, because there is likely to be an unexpected difference of some 20,000 pounds per square inch in the endurance limit of two steels of the same tensile strength, as is shown by the results of Moore, of McAdam, and of this investigation. The

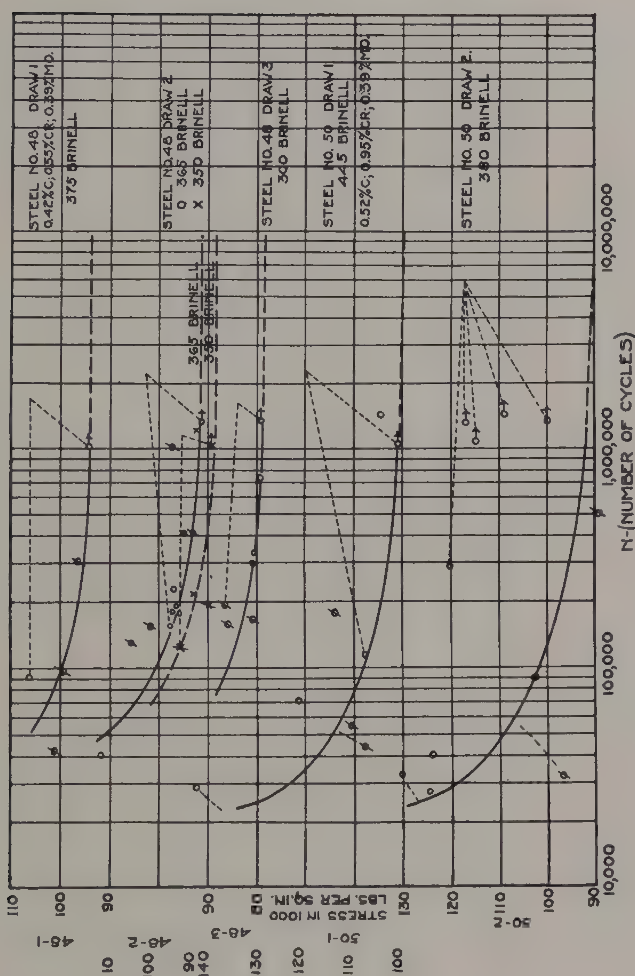


FIG. 39.—Endurance curves for chromium-molybdenum steels.

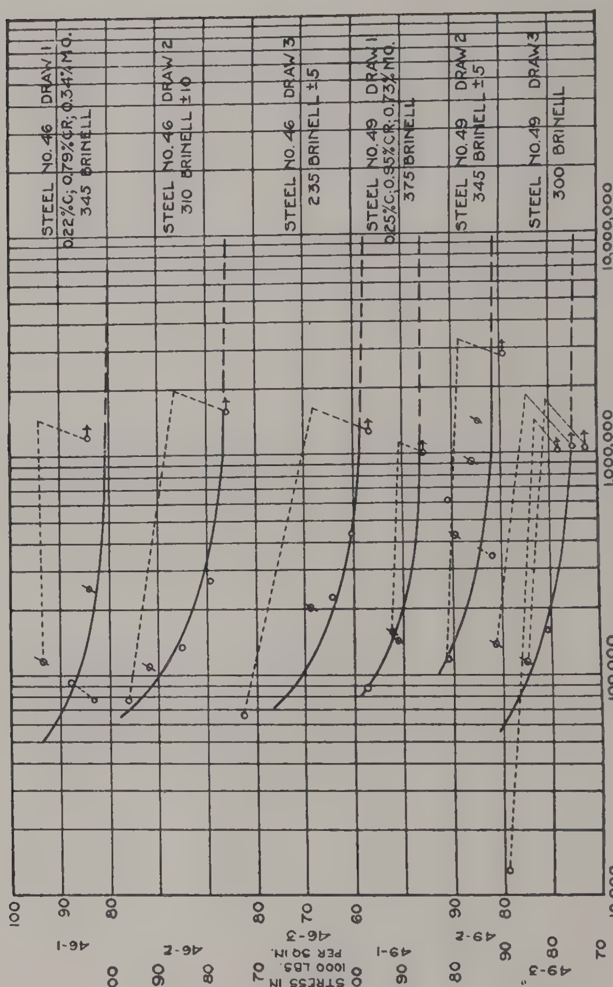


Fig. 40.—Endurance curves for chromium-molybdenum steels.

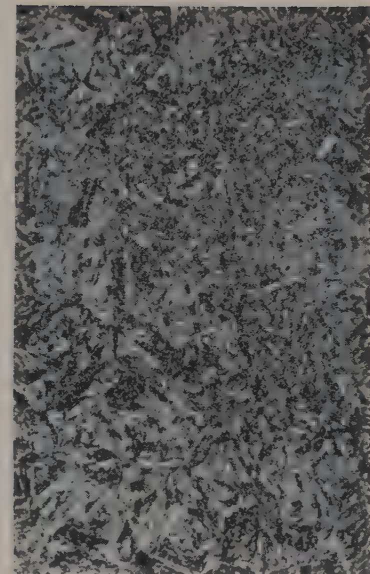
4a

Un-etched. × 100.

Section across direction of rolling, showing inclusions in endurance specimen of 3 per cent. molybdenum steel No. 44.

4b

Structure of 3 per cent. molybdenum steel No. 44.



4c

Structure of high-carbon, chromium-molybdenum steel No. 50; draw No. 1.

Etchant: Alcoholic picric acid. × 500.

PLATE 4.

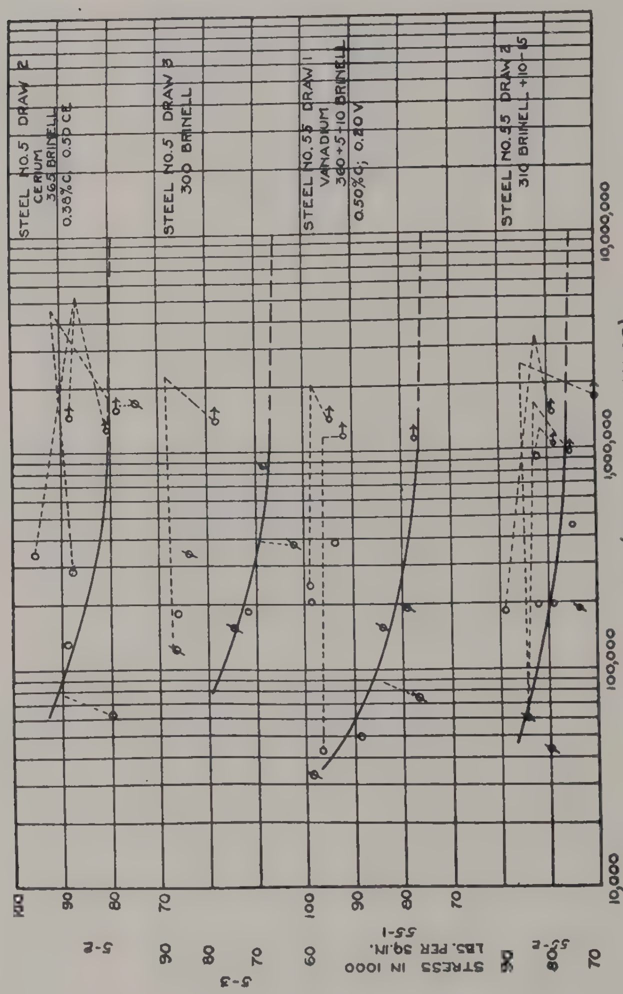


FIG. 41.—Endurance curves for carbon-cerium and carbon-vanadium steels.

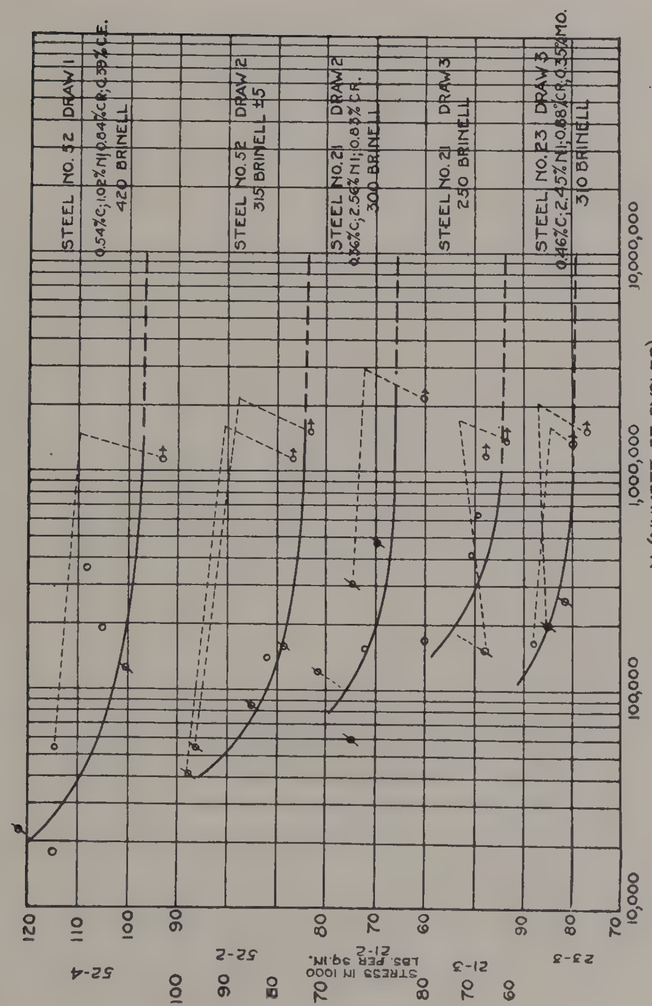


FIG. 42.—Endurance curves for Ni-Cr, Ni-Cr-Mo and Ni-Cr-Ce steels.

same steel in duplicate specimens, supposedly identical, may show a "scatter" nearly as wide as this in extreme cases.

But of the other factors which may enter in, that of the chemical composition is certainly of so small magnitude that it does not manifest itself unmistakably.

When we come to consider heat-treated steels of higher strength, say of "spring temper," quenched and drawn back at temperatures varying with the nature of the steel, it may help to explain the results to assume that unrelieved quenching stresses play a part. By the addition of this internal stress to the applied stress the endurance limit might be reached at a low externally applied stress.

Yet, in a completely reversed endurance test, with equal applied tension and compression stresses, an existing internal tension or compression stress should not alter the *range* of stress. Instead of the tension and compression stresses being equal, one would be raised and the other lowered, the range remaining the same as for the completely reversed stress it is sought to apply. Small changes in the maximum tension or compression are believed to have little effect on the endurance limit if the range is kept constant. One would expect, then, unless the internal stresses are very great indeed, that their effect would be small.

But, when we recall the spontaneous cracking of quenched but untempered specimens of most steels that harden drastically, it is certain that these internal stresses are by no means small. As an example we may cite the results on steel No. 26.

The original No. 26-2, drawn at 525° C. (975° F.) for the usual time of one hour, had a Brinell hardness of 420 but gave an endurance limit of only 87,000 pounds per square inch. (See Fig. 43). One of the No. 26-2 endurance specimens examined several months after the endurance tests were made, showed a longitudinal crack on one end of the piece extending a short distance into the necked portion, but not up to the point of minimum section. It did not cross the line of fracture. This crack certainly did not extend into the neck at the time the specimen was polished, as it would have been readily detected during the regular inspection of the polished area with a x 10 magnifier. The crack probably was not present when the specimen was tested because specimens were always given a final inspection just before being placed in the testing machine.

The existence of this crack is considered rather definite proof that these specimens had considerable internal stress.

Since no more specimens of this draw were available, some extra specimens of steel No. 26, draw No. 1, 1 hour at 430° C. (805° F.), 445 Brinell hardness, were re-drawn in a fused salt bath, being held for

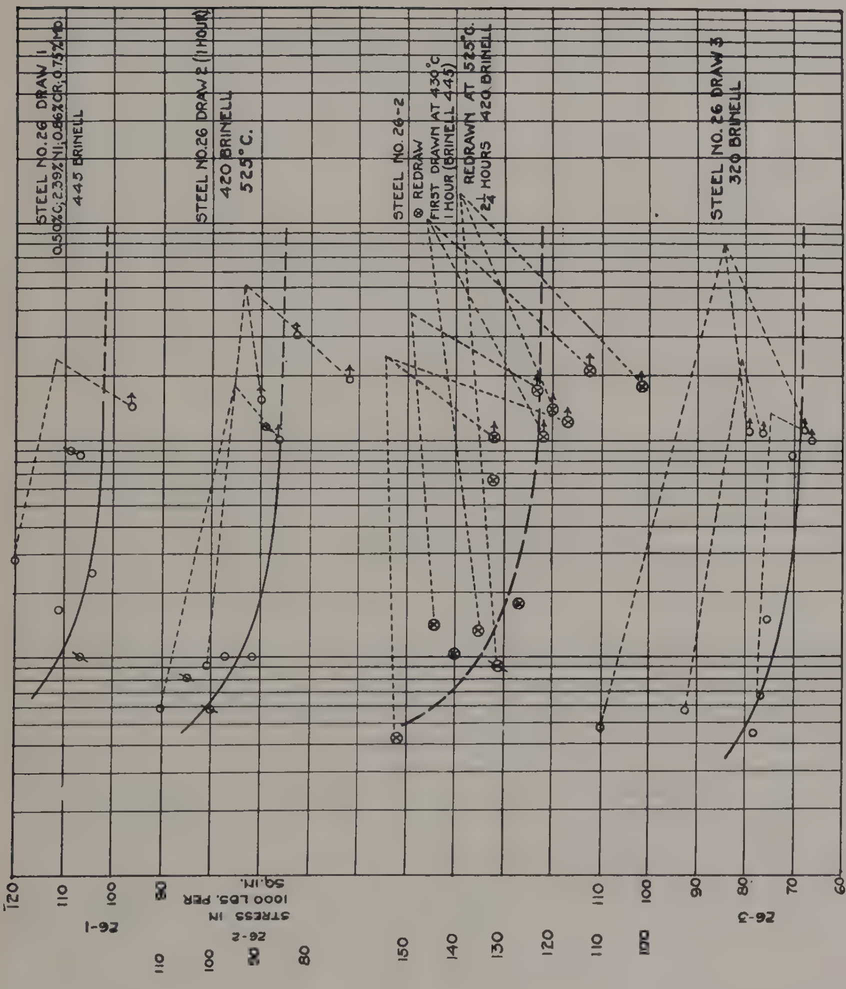


FIG. 43.—Endurance curves for a Ni-Cr-Mo steel at various draws.

2¼ hours at 525° C. (975° F.) and then quenched to avoid oxidation during cooling.

The necked portions of the specimens were deeply repolished to remove any decarbonized layer. These re-drawn specimens, denoted No. 26-2-B,

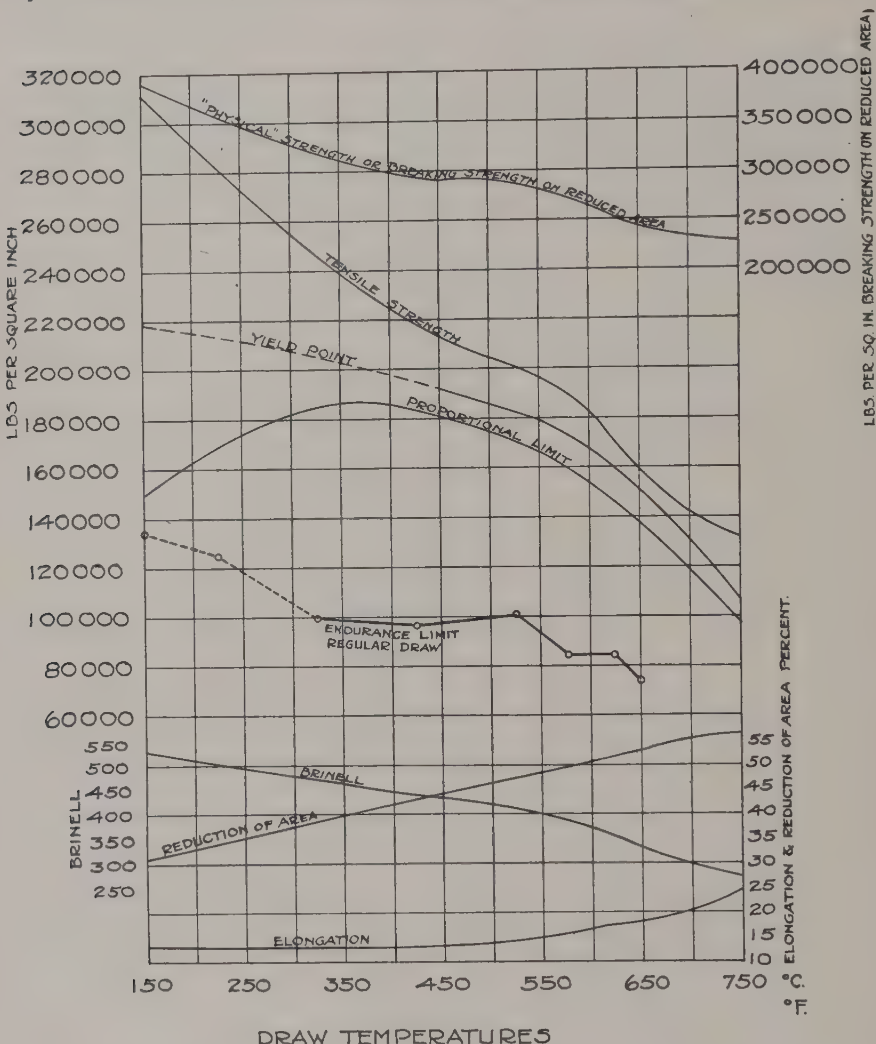


Fig. 44.—Plot of tensile and endurance properties of Ni-Cr-Mo steel No. 22.

had a Brinell hardness of 420, the same as the original shorter draw, No. 26-2.

On endurance test they gave an endurance limit of 123,000 pounds per square inch. Steel of this Brinell hardness would be expected to give an endurance limit of 100,000 to 105,000 pounds per square inch.

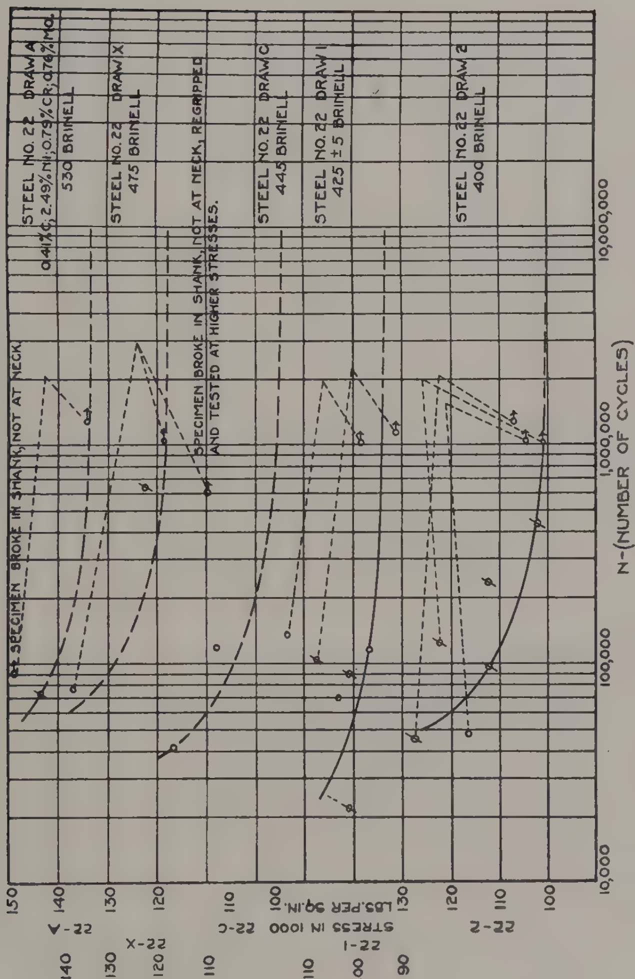


FIG. 45.—Endurance curves for a Ni-Cr-Mo steel at different draws. See Fig. 46.

Redrawing thus raised the endurance limit from 15 per cent. below to 20 per cent. above normal. This phenomenon was studied further with steel No. 22, which was studied at several draw temperatures. The results of the original draws are shown in Fig. 44.

Some specimens of No. 22, draw 2, which gave 400 Brinell hardness after drawing at 525° C. (975° F.) for 1 hour were re-drawn in an electrically heated salt bath, placing them in the bath at 400° C. (750° F.) and raising the bath to 550° C. (1020° F.) in 2½ hours, to 585° C. (1085° F.) in the next hour, and to 600° C. (1110° F.) for about 10 minutes. One lot was then quenched in water and another lot allowed to cool down in the bath with the current off. This cooled only to 100° C. (212° F.) in about 16 hours, cooling being so slow that further tempering was accomplished. The salt bath was then melted and the specimens removed. The Brinell hardness numbers were 385 for the quenched and 365 for the slow cooled specimens.

Endurance tests, Figs. 45, 46, gave an endurance limit of 100,000 pounds per square inch, on the original 400 Brinell hardness specimens; 106,000 on the 385 Brinell hardness re-drawn, and quenched specimens; and 112,000 on the 365 Brinell hardness, re-drawn, slow-cooled specimens.

This gives strong evidence that the removal of internal strains by prolonged high temperature drawing is not accompanied by proportionate softening in these hard molybdenum steels, and that removal of internal stress is accompanied by an increase in endurance limit. The endurance limit is raised in this case, not merely when considered in relation to the hardness, but the limit itself is highest on the steel that was heated the longest, although it is the softest.

It is possible that the prolonged drawing also brought about greater homogeneity of structure and composition.

That this steel, after oil-quenching, is prone to contain quenching stresses, is indicated by a few specimens of great hardness. Two specimens were drawn for 1 hour at 150° C. (300° F.), 225° C. (435° F.) and 325° C. (615° F.) and were placed in oil at 150° C. (300° F.) before they were fully cold after quenching. The other two draws were made on specimens first heated 1 hour at 150° C. (300° F.). The hardness numbers were, respectively, 530, 475, 445. These specimens were ground and polished two months after heat-treatment, and were then uncracked. Six months later when these were tested both 150° C. (300° F.) specimens were found cracked longitudinally but the cracks did not extend far into the necked portions. The specimen at the point of minimum section was uncracked. In testing, these specimens were so oriented that the cracks fell on the neutral or unstressed axis. These longitudinal cracks did not develop farther during testing. One of the specimens in testing at 135,000 pounds per square inch maximum stress

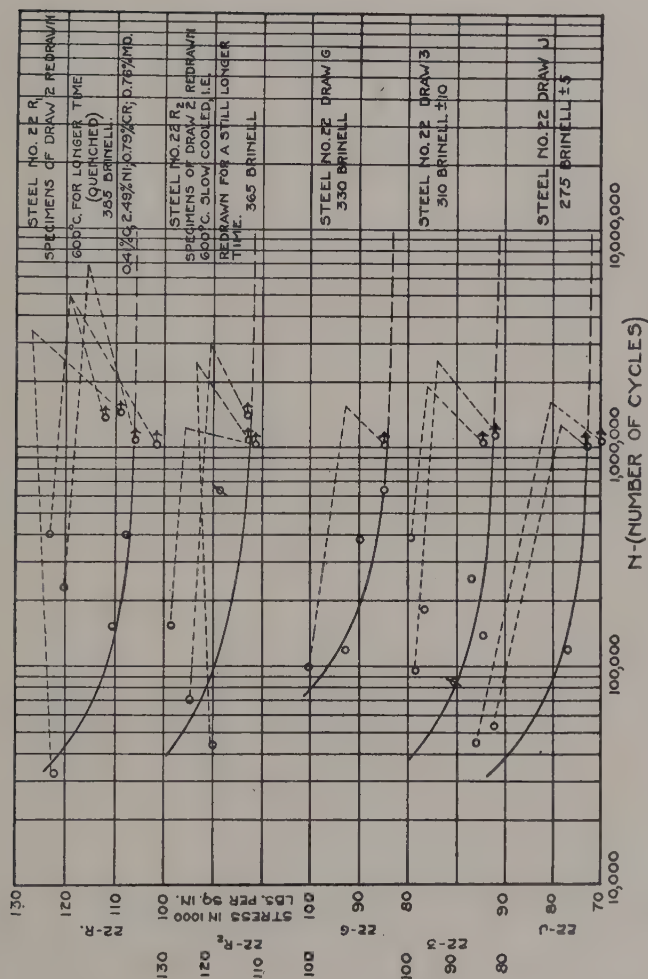


FIG. 46.—Endurance curves for a Ni-Cr-Mo steel at different draws. See Fig. 45.

broke in the grip, but was long enough for re-gripping. The specimen was unbroken after 1¼ million cycles at that stress. On raising the stress to 150,000 pounds the specimen again broke at the shank, not at the neck, after 90,000 cycles, but this time was too short to re-grip. The other specimen broke at the neck after about 70,000 cycles at 145,000 pounds per square inch, but broke above the minimum section.

On the specimens drawn at 225° C. (435° F.) no longitudinal cracks appeared. One specimen broke in the grip during testing, but was long enough for re-gripping.

The specimens drawn at 325° C. (615° F.) did not crack and both broke at the minimum section, but with an unusual, irregular fracture.

The stock of material for testing was insufficient to allow checking up the endurance limit on these very hard steels, but since specimens of both these steels were so brittle as to break in the grips it is obvious that the high indicated endurance values must be discounted for engineering purposes.

Moore and Jasper [172] give curves for three steels at various draw temperatures which show that, at the lowest draw temperatures, the ratio of endurance limit to tensile strength is regularly less than the 50 per cent. value which has been established for the softer steels, and point out that, up to 315° C. (600° F.) relief of internal stress by increased draw temperature is not accompanied by much loss of endurance strength.

Various other steels besides No. 22 tested by the authors confirm this, as is shown below.

No.	Draw No.	Draw Temp. ° C.	Draw Temp. ° F.	Brinell	Endurance Limit
2	3	360	680	420	91,000
2	4	420	790	370	92,000
43	1	425	800	430	94,000
43	2	600	1110	420	99,000
44	1	425	800	420	104,000
44	2	500	930	420	108,000
44	3	575	1065	370	115,000

Further data on this point will be presented in the discussion of the results on test-bars cut from plates, Chapter 10.

It appears that on heat-treated steels drawn at low temperatures, unreleased internal stresses may readily account for low or irregular endurance figures, and that if there is utilized the ability of molybdenum steels to withstand high and prolonged draw temperatures without much softening, steels of spring temper may be produced which will have superior endurance properties because of their strength and hardness and the absence of internal stress. Unless advantage is taken of this ability, the molybdenum steels do not appear to be any better or any worse than other alloy steels in regard to endurance.

In machineable steels the internal stresses are probably of far less

magnitude than they are in the very hard steels. For the steels most used by the engineer it appears that the claims made by some producers for exceptional endurance properties of molybdenum steels were exaggerated, if these steels be compared with others on the basis of strength or hardness.

If, however, the steels are compared at the same heat-treatment, then molybdenum steels could be classed as superior in endurance, because their resistance to tempering makes them harder, stronger and have higher endurance limits than steels of comparable composition but without molybdenum.

Chapter 9.

Normalized Molybdenum Steels.

The comparisons so far made have been confined to heat-treated steels. Some of the steels were also tested in the normalized condition but only a few of these were given endurance tests.

The data for the normalized specimens together with scattering tests on annealed specimens are plotted in Fig. 47 and collected in Table 12. Of these steels Nos. 40 and 44 were cooled in the furnace with the door open, a procedure intermediate between normalizing and annealing.

Considering the tensile tests, one outstanding point is noted. The stress-strain diagram (Fig. 48) for the normalized vanadium steels shows a sharp break at the yield point; the proportional limit, yield point by extensometer, and yield point by drop-of-beam all falling within a narrow stress range. The elastic ratio, though not as high in heat-treated steels, runs about 70 per cent. to 75 per cent.

On the other hand, a yield point by drop-of-beam was observable only in the case of the normalized molybdenum steel of lowest molybdenum content, and in the others the stress-strain diagram shows a gradual curvature, like that of a quenched, untempered, hard steel or of a non-ferrous alloy. The "yield point" by extensometer is then not a true yield point, although this heading has been retained for the sake of uniformity. The elastic ratio calculated from this extensometer yield point lies around 60 per cent. as a maximum, and in the case of steels No. 10 and No. 50 falls to around 30 per cent. The proportional limit on steel No. 10, is at 25,000-30,000 pounds although the tensile strength is 150,000-160,000 pounds and the elastic ratio calculated on proportional limit lies around 17 per cent.

Moreover steels Nos. 10 and 50 give low elongation, low reduction of area and break with a flat, brittle fracture. Plate 5a, p. 176, shows the fracture of No. 10 quenched from 900° C. (1650° F.), which gave 5 per cent. elongation 4½ per cent. reduction of area. In most cases, however, the normalized molybdenum steels show considerable elongation but slight reduction; they stretch more than they neck, which is of course in keeping with their stress-strain diagrams.

The Brinell hardness of the normalized molybdenum steels gives a clue to the reason for their behavior. Those with flat fractures run around

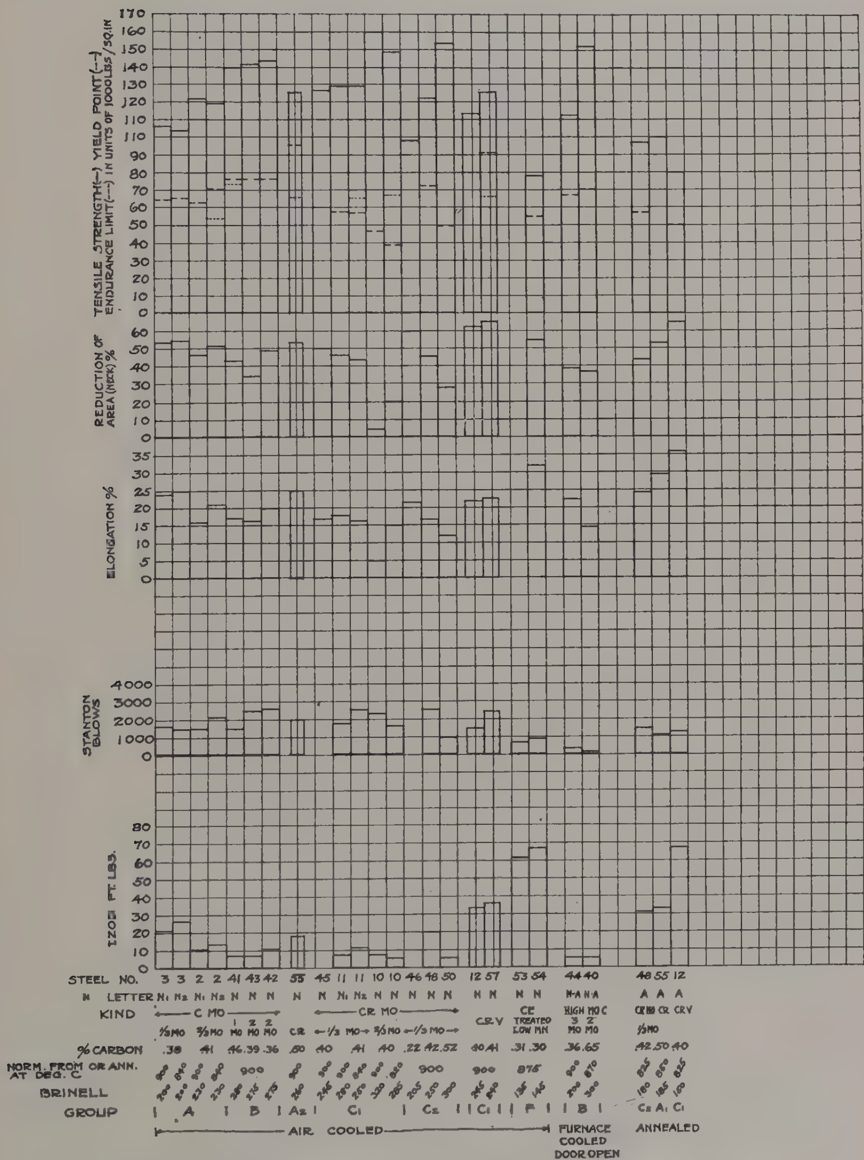


FIG. 47.—Plot of properties of normalized and annealed steels.

TABLE 12
NORMALIZED STEELS

No.	C	Mo	Cr	V	°C.	°F.	Medium	Brinell	P. L.	Y. P. ext.	Y. P. drop beam	T. S.	Elong. %	R. A. %	Fracture	M. I.	El. Ratio	Stanton Test Brinell	Stanton Test Blows	Izod Test Brinell	Izod Test Ft. lbs.	Endurance Test Brinell	Endurance Test Endurance Limit
3	.38	.37	......	......	900	1650	air	200	60,000	65,500	67,500	107,500	24.0	54.0	part cup	45	61	(200)	1625	(200)	22	......	no specimen
3	.38	.37	......	......	840	1545	air	210	60,000	65,500	65,500	104,000	25.0	54.5	do.	47	63	(205)	1480	(190)	27	180	50,000
2	.41	.67	......	......	900	1650	air	230	50,000	62,500	N	121,500	16.0	46.5	do.	28	51	230	1520	(230)	11.5	......	no specimen
2	.41	.67	......	......	840	1545	air	230	67,500	71,000	N	119,000	21.0	51.5	do.	41	60	230	2170	230	14	225	54,000
43	.39	1.90	......	......	900	1650	air	275	S	75,000	N	141,500	16.5	35.2	do.	28	53	300	2450	(280)	7	......	no specimen
42	.36	2.05	......	......	900	1650	air	275	S	75,000	N	143,250	20.0	49.1	do.	43	52	285	2575	260	11	......	no specimen
44	.36	3.00	......	......	900 with	1650 door	furnace open	205	S	67,500	N	112,500	22.5	39.3	do.	33	60	195	392	(200)	6	......	no specimen
39	.50	1.15	......	......	900	1650	air	295	S	75,000	N	149,000	19.5	41.4	do.	38	50	295	521	(295)	9	......	no specimen
40	.65	1.90	......	......	870 with	1600 door	furnace open	300	S	70,000	N	152,000	14.5	37.2	do.	26	46	300	209	295	6	......	no specimen
55	.50	......	......	.20	900	1650	air	260	95,000	96,000	97,000	125,000	25.0	54.0	do.	60	76	270	1980	230	19	250	65,000
45	.40	.30	.88	......	900	1650	air	245	S	60,000	N	127,000	17.3	50.1	do.	33	47	no spe	cimen	no spe	cimen	no spe	cimen
11	.41	.36	.89	......	900	1650	air	280	50,000	57,500	N	129,500	18.0	45.5	part cup	31	44	(280)	1815	(280)	7.5	......	no specimen
11	.41	.36	.89	......	840	1545	air	250	47,500	57,500	N	129,500	16.5	44.0	do.	28	44	(245)	2445	(245)	12	240	65,000
10	.40	.68	.95	......	900	1650	air	320	30,000	47,500	N	160,000	5.0	4.5	flat	9	30	(320)	2275	(320)	7.5	......	no specimen
10	.40	.68	.95	......	820	1510	air	285	25,000	38,500	N	148,500	15.0	20.0	do.	18	26	300	1640	275	6	255	67,000
12	.40	......	.93	.20	900	1650	air	245	S	80,000	82,500	113,500	21.5	62.3	part cup	55	71	(245)	1520	(245)	33.5	......	no specimen
57	.41	......	.93	.16	900	1650	air	235	85,000	91,000	94,500	126,000	22.5	62.5	do.	65	72	240	2360	245	36	225	66,000
48	.42	.39	.55	......	900	1650	air	250	S	72,500	N	122,250	17.0	45.5	do.	30	59	(250)	2515	(250)	20	......	no specimen
50	.52	.39	.95	......	900	1650	air	300	S	50,000	N	153,500	12.0	28.0	flat	17	33	320	1000	(310)	5	......	no specimen
48	.42	.39	.55	......	Annealed 825	1515	furnace	180	S	57,500	59,750	97,000	24.5	43.3	part cup granular	33	59	(180)	1450	(180)	30.5	......	no specimen
55	.50	......	......	.20	850	1560	furnace	195	70,000	70,000	70,000	100,000	29.5	53.2	part cup	52	70	185	1110	175	33.5	......	no specimen
12	.40	......	.93	.20	825	1575	do.	150	S	50,000	50,000	80,000	36.0	64.7	do	67	63	150	1230	(150)	66.5	......	no specimen

S—"Scissors" extensometer used. N—none noted.

300 Brinell hardness. Consequently they must have air-hardened to some degree. If we then consider the critical point curves we find that when the composition of the steel is high enough in carbon and molybdenum, or in carbon, chromium and molybdenum to produce a marked propensity for hardening as shown by the appearance of Ar″ on cooling from high temperatures, the normalized specimens show lowered ductility and elastic ratio.

Normalizing of steels Nos. 2, 3, 11 and 10 from a lower temperature, the first three from 840° C. (1545° F.) the last from 820° C. (1510° F.) was tried. No marked improvement, except in the ductility on the last steel was thereby obtained. At the cooling rate obtaining in normalizing

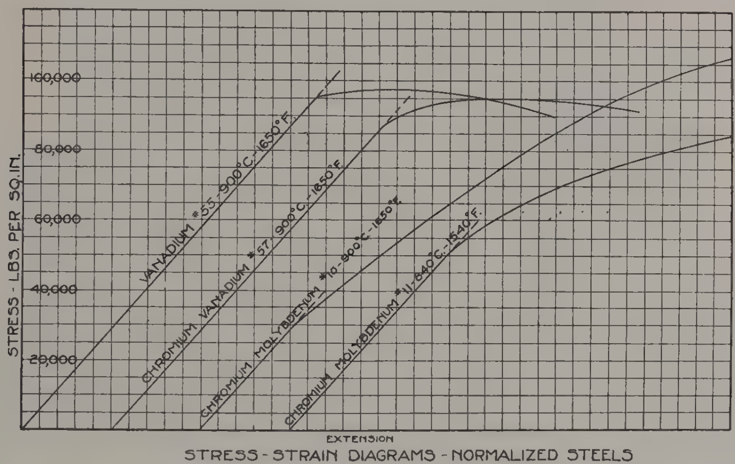


FIG. 48.—Stress-strain diagrams—normalized V, Cr-V and Cr-Mo steels.

bars of this size (¾ inch diameter) Ar″ doubtless still appears even from these temperatures. The cooling rate in the critical point tests was of course much slower, so that Ar″ only appears when the steel has a decidedly marked propensity for hardening.

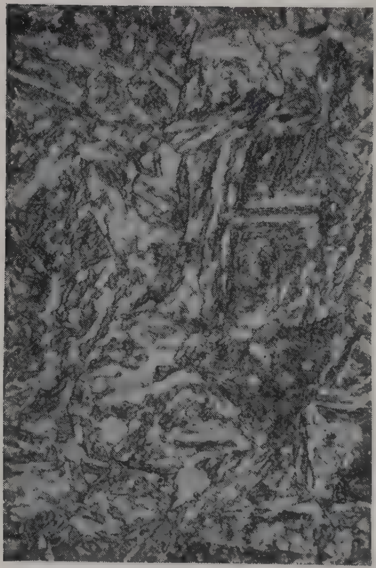
The structure of steel No. 2, normalized from 900° C. (1650° F.) is shown in Plate 5b. That of a 0.52 per cent. C, 0.95 per cent. Cr, 0.39 per cent. Mo (No. 50) (Plate 5c) steel and of a 0.40 per cent. C, 0.95 per cent. Cr, 0.68 per cent. Mo, (Plate 6a) both normalized from 900° C. (1650° F.) show that the structures of all these normalized molybdenum steels are very different from those of normalized carbon-vanadium (Plate 6b) or normalized chromium-vanadium (Plate 6c).

The radial fracture of steel No. 10 (Plate 5a) suggested that the specimen might be dirty, and on examination of the specimen close to the focus of the radial lines, it was shown to be dirty (Plate 7a). On the other hand, examination of a number of the early un-necked endurance

× 5.

5a

Brittle fracture of tensile test-piece of chromium-molybdenum steel No. 10, normalized from 900° C. (1650° F.).



5b

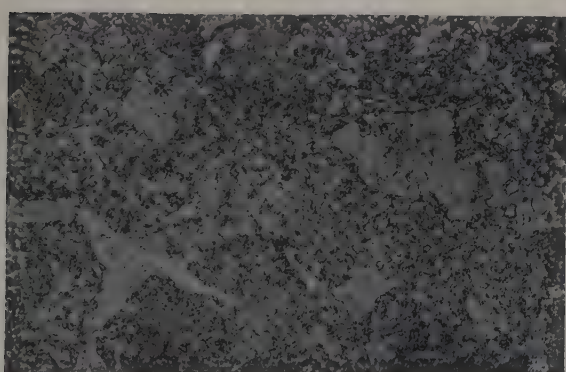
5c

Etchant: Alcoholic nitric acid. × 500.

Structure of plain molybdenum steel No. 2, normalized from 900° C. (1600° F.).

Structure of chromium-molybdenum steel No. 50, normalized from 900° C. (1650° F.).

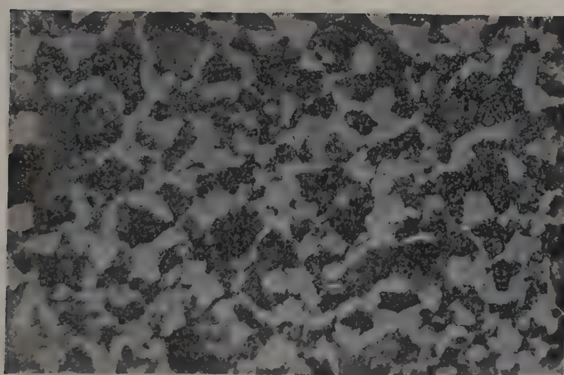
PLATE 5.



6a

Etchant: Alcoholic nitric acid.

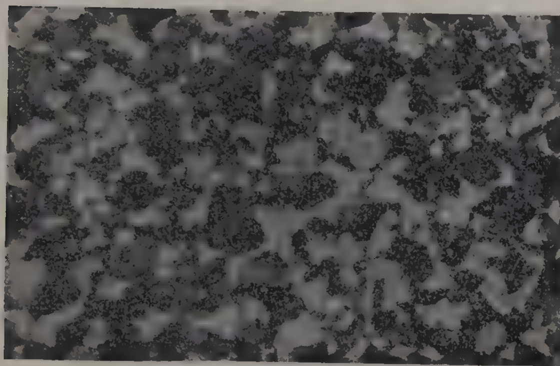
Structure of chromium-molybdenum steel No. 10.



6b

Etchant: Alcoholic picric acid.

Structure of carbon-vanadium steel No. 55.



6c

Etchant: Alcoholic picric acid. All × 500.

Structure of chromium-vanadium steel No. 57.

PLATE 6.—Structure of steels—all normalized from 900° C. (1650° F.).

7a

7b

7c

All un-etched. × 100.

7a. Section across direction of rolling, showing inclusions in tensile test-piece of steel No. 10, normalized. Fracture shown in Plate 5a.

7b. Representative area, typical of many specimens of steel No. 10.

7c. Section across direction of rolling, showing inclusions in steel No. 50.

PLATE 7.—Inclusions in chromium-molybdenum steels.

specimens of steel No. 10, indicated that the steel was exceptionally clean, Plate 7b, showing a representative field.

Plate 7c shows the normalized tensile specimen of steel No. 50, while Plates 8a and 8b show two spots on tht same surface of the normalized tensile specimen of steel No. 57.

Steel No. 55 also shows variability in cleanliness. Plate 9-a shows a surface on an endurance specimen and Plate 9b one of the normalized tensile specimens of this steel, while Plate 9c shows a giant inclusion (at 100 diameters) on the same surface as Plate 9b. This surface was taken at the shoulder of the normalized tensile specimen, and the huge inclusion, being in an unstressed portion, did not affect the observed tensile strength. This steel is a carbon-vanadium steel, made in the electric furnace, by a commercial producer of high grade alloy steel.

Obviously, neither electric melting nor the presence of vanadium is sufficient to insure the absence of even such huge inclusions as this.

Comparing the Stanton results for normalized steels with the Stanton curve for heat-treated steels (Fig. 30, p. 141) it is seen that the specimens cooled in the furnace with the door open (N-A) show almost no resistance to repeated impact and that steel No. 10, the one with the least ductility falls down in comparison with heat-treated steels of the same hardness. Two of the normalized vanadium steels (Nos. 12 and 55) also fall down while one (No. 57) does not. Some of the normalized molybdenum steels fall down and some do not.

In Fig. 31, p. 142, are plotted the Izod tests. By comparison with the curve for heat-treated steels, it is seen that the notched-bar value of all the normalized or annealed steels is low. The two steels (Nos. 40 and 44) cooled in the furnace with the door open (N-A) fall down as they did on the Stanton test.

Normalized vanadium steel No. 55-N is only slightly above the average curve for the normalized molybdenum steels. No. 48-N is the only molybdenum steel to lie well above the curve while two normalized chromium-vanadium steels 12-N and 57-N lie above it, although far below the curve for heat-treated steels.

Endurance tests were made on too few normalized steels to allow drawing many conclusions. But the results on normalized molybdenum or chromium-molybdenum steels Nos. 2, 3, 10, and 11 fall close to the curve of Fig. 32 (P. 147). The remarkable thing about Nos. 10 and 11 in the normalized state is that the endurance limit is well above the static proportional limit or even above the "yield point by extensometer," *i.e.*, what would be termed the "elastic limit" in most commercial testing. That is, in repeated bending these steels will withstand (see Figs. 49 and 50) for two or three million alternations and probably indefinitely, stresses at which their stress-strain diagrams (Fig. 48, p. 175) show a very decided curvature.

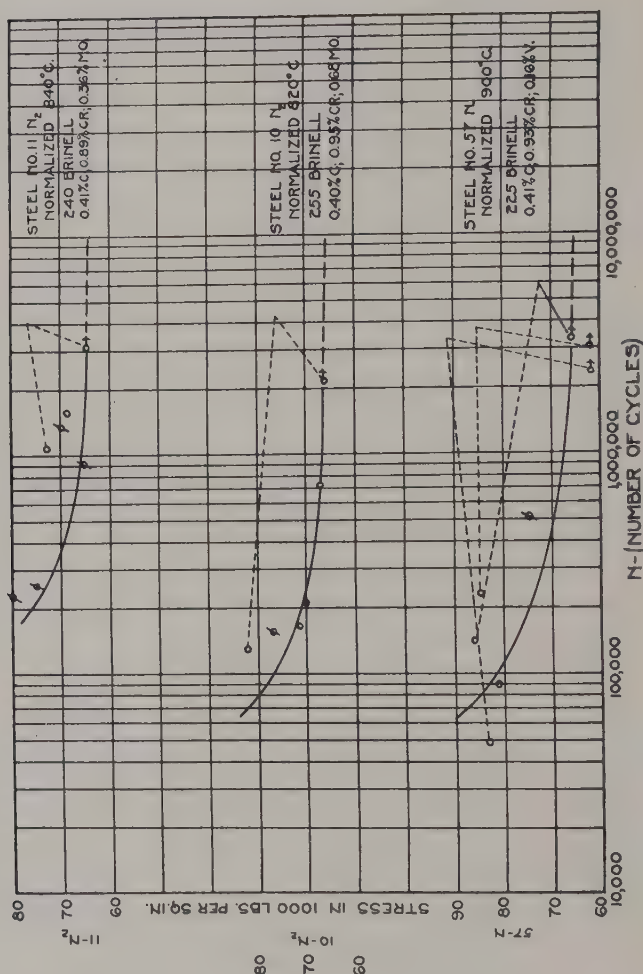


Fig. 49.—Endurance curves for normalized Cr-Mo and Cr-V steels.

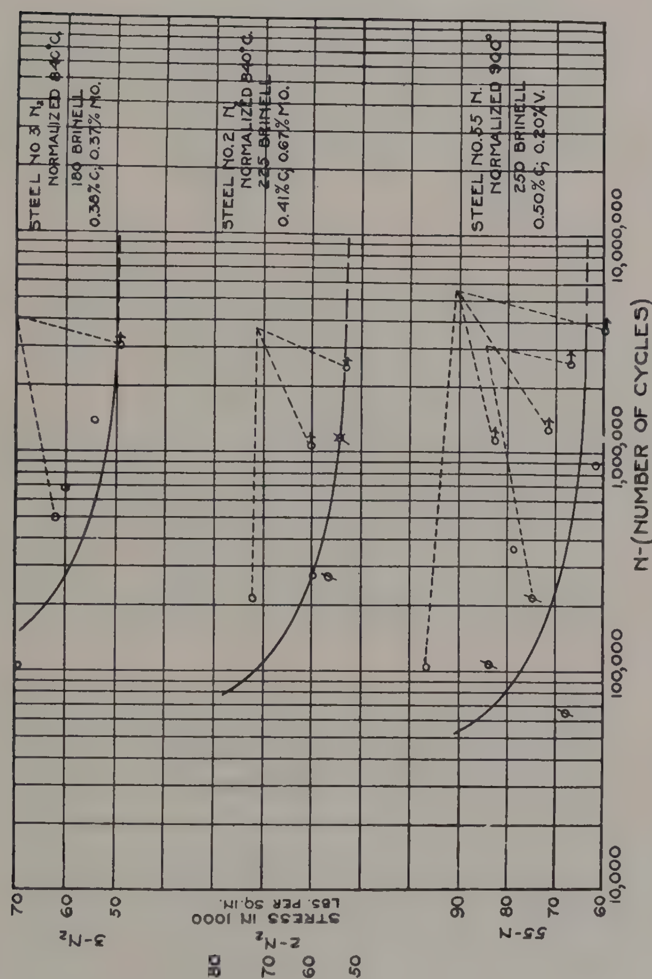
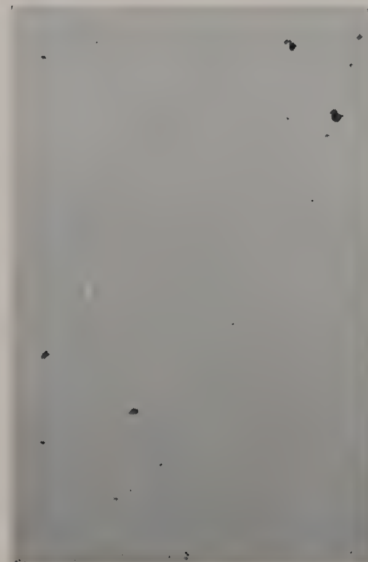


FIG. 50.—Endurance curves for normalized molybdenum and vanadium steels.

8a

Section across direction of rolling, showing relatively dirty area in specimen of chromium-vanadium steel No. 57.



8b

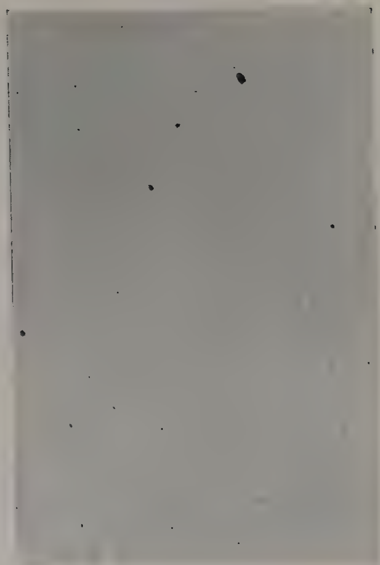
Section across direction of rolling, showing relatively clean area in specimen of steel No. 57.

8c

Section parallel to direction of rolling, showing inclusions in cerium steel No. 5.

All un-etched. × 100.

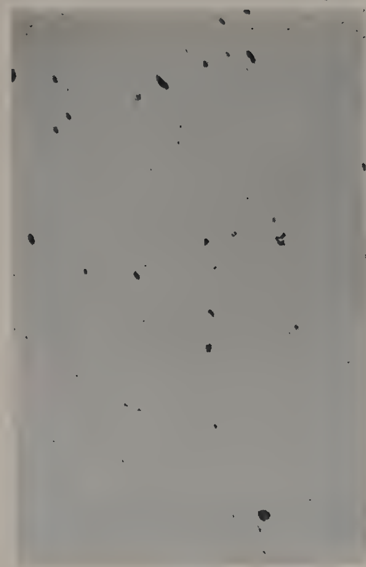
PLATE 8.—Inclusions in steels.



9a

× 100.

Typical area in one specimen of steel No. 55 electric carbon-vanadium steel from commercial producers.



9b

× 100.

Section across direction of rolling, showing inclusions in another specimen of steel No. 55.

9c

× 500.

Section across direction of rolling, showing inclusions in another specimen of steel No. 55.

All un-etched.

PLATE 9.—Inclusions in carbon-vanadium steel.

Aitchison (10, pp. 108, 135, 208) shows that the endurance limit of air-hardening nickel-chromium steel is above the static proportional limit, for steels not drawn or drawn at temperatures below 350° C. (660° F.). He also shows that stress-strain curves of the type found for these normalized molybdenum steels are obtained for hardened and un-tempered or but slightly tempered steels. He then explains that the vague values obtained for proportional or elastic limit and yield point in such cases may be due to the release of internal hardening strains during testing, the steels slightly deforming and retaining that tiny deformation when the stress is released. A similar deformation would also be found in compression, *i.e.*, the stress-strain diagram shows a hysteresis loop.

Both Aitchison (10, p. 135) and Jenkin (162) show that cyclic stressing, as in the endurance test, closes up the hysteresis loop; so that a steel of this sort after cyclic stressing would show a static proportional limit equal to the maximum cyclic stress previously applied.

This similarity to untempered, fully air-hardened, steels shown by these air-cooled, partly hardened, molybdenum steels, although the latter are much softer, indicates that the cause of the poor showing of the normalized molybdenum steels is due to their propensity for hardening. This is an advantage in heat-treatment, but a disadvantage for normalizing.

But this behavior is not peculiar to molybdenum steels, it is common to all the strongly-hardening steels according to the degree to which Ar″ is developed in air-cooling. For example, the British Engineering Standards Association (117) gives the following for normalized 1⅛ inch diameter bars:

C	Ni	Cr	Normalized ° C.	Normalized ° F.	Brin.	Y. P.	T. S.	El. Per Cent.	R. A. Per Cent.	Izod Foot, Pounds
.35	....	....	970	1780	145	49,000	76,000	34	58	26
.38	3.65	....	860	1580	195	60,000	98,000	28	56	4½
.38	1.72	1.65	850	1560	440	......	224,000	12	38	5
.31	3.27	.82	820	1510	340	......	170,000	15	40	6
.32	3.70	1.42	850	1560	475	......	258,000	13	40	18

Carbon-vanadium and chromium-vanadium steels are noteworthy for giving better results in the normalized condition than can be obtained from normalized carbon steels, so that they are of value for heavy or complicated pieces which cannot readily be heat-treated. The commercial chromium-molybdenum steels are obviously less suited for such a purpose, although a small molybdenum content, too low to produce a tendency toward air-hardening, might be of value.

The commercial molybdenum steels chiefly fall into the class of alloy steels which demands heat-treatment in order to develop the best combination of properties of which they are capable.

Chapter 10.

Tests of Longitudinal and Transverse Specimens.

Because of Cohade's claim (135) that "molybdenum, even in small quantities, accentuates the bad results of transverse tests" it was decided to include in the test series some direct comparisons of properties of longitudinal and transverse specimens cut from adjacent portions of the ingot. For this purpose there were prepared the following steels; group C, steels No. 27 to 30 containing about 0.40 per cent. carbon, 0.90 per cent. chromium as the base steel, the individual members of the group having added, respectively, 0.25 per cent. vanadium, 0.35 per cent. molybdenum and 0.75 per cent. molybdenum; group E steels No. 32 to 37, with 0.40 per cent. carbon, 2.50 per cent. nickel, 0.85 per cent. chromium as the base steel, the individual members of the series having added, respectively 0.25 per cent. vanadium, 0.35 per cent. molybdenum, 0.75 per cent. molybdenum, and 0.20 per cent. cerium.

These steels were cast in 3 inch x 6 inch ingots which were rolled down to 0.6 inch x 6 inch plates without any cross-rolling whatever, the idea being thus to intensify the usual differences between specimens taken with the direction and across the direction in which more of the working is done.

The first series was oil-quenched from 900° C. (1650° F.) and all four steels were drawn at the same temperature, 500° C. (1020° F.). This treatment gave harder and stronger specimens from the vanadium and molybdenum steels, especially the latter, than from the plain chromium, and in order to get specimens more nearly comparable in strength the higher molybdenum steel (No. 28) was also drawn at 625° C. (1155° F.) but even this did not bring the strength down to that of the plain chromium.

The second series was oil-quenched from 805° C. (1480° F.) with the exception of one steel (No. 37) of higher carbon content than the balance, which was quenched from 790° C. (1450° F.). Instead of drawing all the steels at the same temperature, this series was drawn at varying temperatures, an attempt being made to get a Brinell hardness of 340 on all. On this second series of plates, containing both nickel and chromium, the specimens were cooled with the furnace after the draw instead of being taken out and cooled in air as was the case on all other lots.

Full data from the tensile tests on these steels is given in Table 13

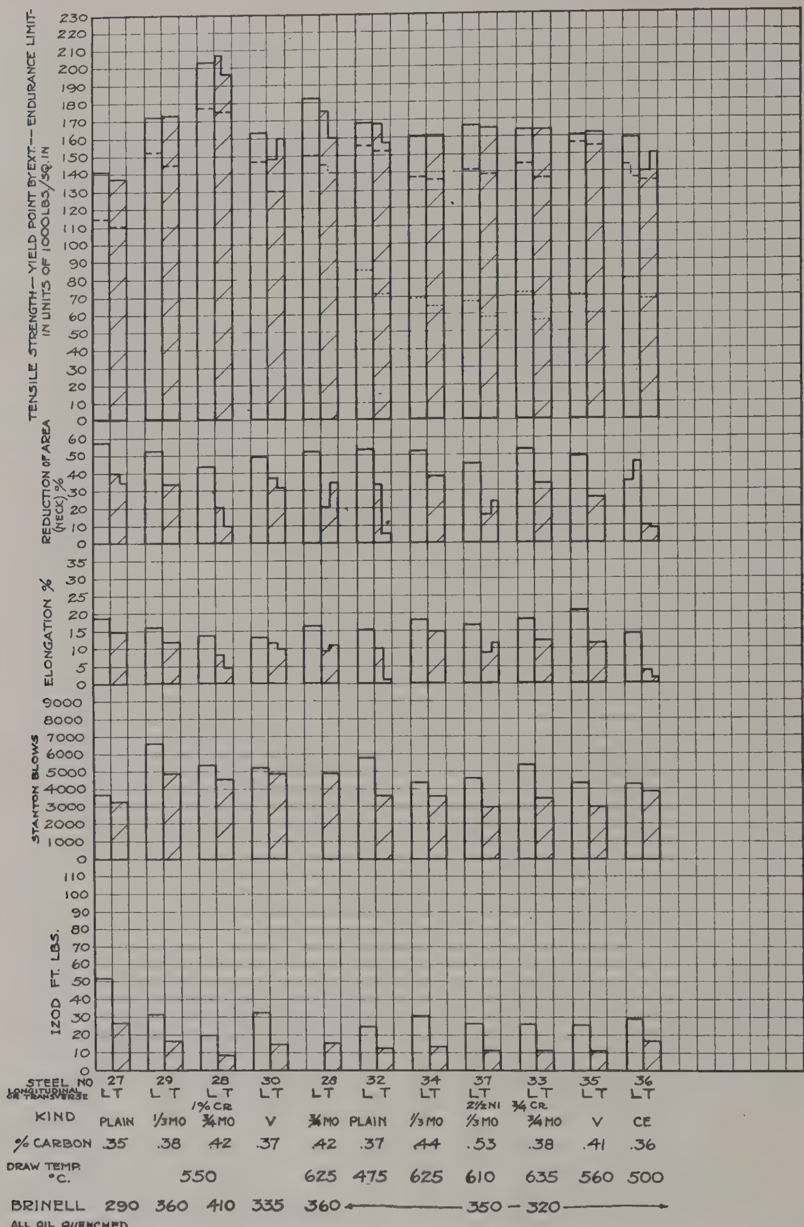


FIG. 51.—Properties of longitudinal and transversal specimens, alloy steel plates.

TABLE 13

MECHANICAL TEST DATA ON LONGITUDINAL AND TRANSVERSE SPECIMENS FROM ROLLED PLATES

No.	Direction	Composition and History: Composition (Per Cent) C	Ni	Cr	Mo	V	Ce	Heat Treatment Quench °C.	Medium	Draw °C.	Tensile Data: Brinell Hardness	Prop. Lim. lbs./sq. in.	Yield Point Extensometer	Yield Point Drop Beam	Maximum Tensile Strength Orig. Area	Elongation, % in 2"	Red. Area Neck %	Red. Area Fracture %	Merit Index	Elastic Ratio	Breaking Strength Orig. Area	Breaking Strength Red. Area	Nature of Fracture	Impact Data: Brinell Hardness Stanton Specimen	Stanton Blows to Fracture	Brinell Hardness Izod Specimen	Izod Test Ft. Lbs.	Endur. Data: Brinell Hardness Endurance Specimen	Endur. Limit Upton-Lewis Test Lbs. Sq. In.[b]	Remarks
27	L*	.35	....	.94	...	...	...	900	oil	550	290	107,500	115,000	120,000	141,000	19.2	57.3	56.5	57	82	100,500	231,000	Star	285	3750	285	52.5	270	U***	
27	T**	...	....	...	...	...	...	"	"	"	295	100,000	110,000	119,000	137,250	14.8	40.3	39.0	30	80	119,750	196,000	Cupped silky	280	3350	(280)	27.5	270	U	
	"	...	....	...	...	...	...	"	"	"	"	"	"	"	"	"	34.0	32.8	27	"	115,750	170,000	Cupped silky, seam							
29	L	.38	....	.84	.35	...	...	"	"	"	355	147,500	152,500	155,000	171,500	16.0	51.9	51.6	54	89	127,500	264,000	Star	370	6600	(360)	31.5	355	U	
29	T	...	....	...	...	...	...	"	"	"	370	137,500	145,000	150,000	173,000	11.8	33.3	31.5	28	84	156,000	228,000	Cupped silky	360	4900	(360)	16.5	355	U	
28	L	.42	....	.93	.73	...	...	"	"	"	400	155,000	177,000	N	203,000	13.7	43.3	41.6	39	87	160,000	272,000	Cupped silky	395	5350	(400)	21	385	U	Stanton tests varied 4409 to 5920
28	T	...	....	...	...	...	...	"	"	"	425	150,000	175,250	N	207,000	8.5	20.5	19.7	20	85	195,000	243,000	" slightly woody	400	4590	(400)	9.5	385	U	Stanton tests varied 4121 to 4864
	"	...	....	...	...	...	...	"	"	"	410	"	"	"	196,500	4.5	9.5	8.8	9	89	196,500	217,000	Flat, woody							
28	L	...	....	...	...	...	...	"	"	625	360	140,000	150,000	N	182,250	16.5	51.9	50.2	57	83	135,000	271,000	Cupped—serrated	N.B.	......	N.B.	....	N.B	..	
28	T	...	....	...	...	...	...	"	"	"	365	140,000	145,000	N	174,500	9.5	20.5	16.4	19	83	165,500	197,500	Cupped—silky	380	4965	365	16	360	U	
	"	...	....	...	...	...	...	"	"	"	345	135,000	140,000	"	159,000	11.0	34.0	29.3	25	88	144,500	204,000	Cupped—silky							
30	L	.37	....	.97	...	.24	...	"	"	550	335	140,000	147,500	152,250	163,250	13.5	49.1	48.0	41	90	122,750	236,000	Star	325	5310	(325)	33	320	U	Stanton tests varied 4731 to 6144
30	T	...	....	...	...	...	...	"	"	"	320	125,000	130,000	139,000	149,000	12.0	37.2	35.9	27	87	127,750	199,500	Cupped silky	325	3850	(325)	15	320	U	Stanton tests varied 3549 to 4080
	"	...	....	...	...	...	...	"	"	"	340	"	"	"	160,000	10.0	30.7	29.7	25	82	140,500	200,000	" slightly woody	.....	......	......	....	....	....	Izod tests varied 12 to 18

TABLE 13 (Continued)

MECHANICAL TEST DATA ON LONGITUDINAL AND TRANSVERSE SPECIMENS FROM ROLLED PLATES

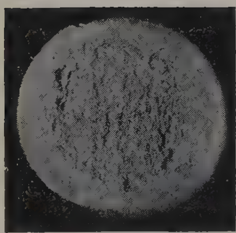
No.	Direction	Composition and History: Composition (Per Cent) C	Ni	Cr	Mo	V	Ce	Heat Treatment: Quench °C.	Medium	Draw °C.	Tensile Data: Brinell Hardness	Prop. Lim. lbs./sq. in.	Yield Point Extensometer	Yield Point Drop Beam	Maximum Tensile Strength Orig. Area	Elongation, % in 2"	Red. Area Neck %	Red. Area Fracture %	Merit Index	El. Ratio	Breaking Strength Orig. Area	Breaking Strength Red. Area	Nature of Fracture	Impact Data: Brinell Hardness Stanton Specimen	Stanton Blows to Fracture	Brinell Hardness Izod Specimen	Izod Test Ft. Lbs.	Endur. Data: Brinell Hardness Endurance Specimen	Endur. Limit Upton-Lewis Test Lbs. Sq. In[b]	Remarks
32	L*	.37	2.49	.83	...	...	...	805	oil	475	350	150,000	155,000	158,500	168,500	15.5	53.0	50.2	53	92	118,500	238,000	Star	350	5760	350	25	350	85,000	Steels 32–37 furnace cooled after draw
32	T**	...	...	...	...	...	...	"	"	"	350	147,500	152,500	158,500	168,000	10.0	33.5	31.4	24	91	150,500	219,000	Cupped sl. woody	340	3890	340	12	345	70,000±[b]	
	"	...	...	...	...	...	...	"	"	"	"	"	"	157,500	157,000	1.0	4.8	0.7	2	97[a]	157,000	158,000	Flat, woody							
34	L	.44	2.44	.82	.37	...	...	"	"	625	340	132,500	137,500	141,000	161,000	18.5	52.0	50.9	58	85	119,000	243,000	Star	340	4340	340	31.5	320	69,000	
34	T	...	...	...	...	...	...	"	"	"	340	132,000	136,000	143,000	161,000	15.0	37.5	35.7	36	85	148,000	230,000	Cupped dull	340	3640	340	12.5	320	65,000	
37	L	.53	2.52	.83	.34	...	...	790	"	610	345	135,000	141,000	146,000	166,500	17.0	45.1	43.0	48	85	130,500	229,000	Cupped—serrated	345	4550	340	27	330	67,000	
37	T	...	...	...	...	...	...	"	"	"	345	135,000	139,000	145,000	165,500	9.0	15.5	13.5	16	84	152,250	176,000	" slightly woody	350	2980	350	11	310	58,000	
																11.5	22.7	20.1	23	84	150,500	189,000	" slightly woody							
33	L	.38	2.53	.78	.75	...	...	"	"	635	340	139,000	145,000	152,500	164,000	18.5	52.5	50.9	60	88	120,000	244,000	Cupped—Star	350	5360	340	26.5	335	72,000±	
33	T	...	...	...	...	...	...	"	"	"	340	132,500	137,500	152,000	164,000	12.5	34.1	31.6	29	84	143,000	210,000	Cupped, dull	350	3510	340	11	340	56,000	
35	L	.41	2.52	.85	...	.19	...	805	"	560	340	151,000	156,000	160,500	161,000	16.0	48.6	47.8	49	97	120,000	230,000	Star—oblique	340	4185	340	26	340	71,000	
35	T	...	...	...	...	...	...	"	"	"	340	150,000	155,000	160,000	162,500	11.5	26.0	24.0	25	95	148,000	195,500	Cupped trace w'dy	340	3040	340	11	320	60,000±	
36	L	.36	2.46	.92	...	...	.19	"	"	500	330	139,500	145,000	146,750	160,000	14.5	34.5	32.3	33	90	133,000	198,000	Cupped—irreg s'm	330	4290	330	29	340	80,000	
		...	...	...	...	...	...	"	"	"	"	132,500	137,000	146,750	158,500	14.5	44.9	44.0	40	86	118,500	212,000	Cupped star, seam							
36	T	...	...	...	...	...	...	"	"	"	320	131,750	135,000	140,000	140,000	4.0	10.2	8.0	5	96[a]	138,000	150,000	Cupped, laminated	330	3875	330	17	330	69,000±	
		...	...	...	...	...	...	"	"	"	"	131,750	135,000	140,000	150,500	2.0	8.5	6.1	3	90	150,500	160,000	Cupped, irregular							

a High elastic ratio due to low tensile strength; bar broke early on account of large inclusion, 32T, and of many small inclusions, 36T.
b These endurance limits are for the original draw. For results after redrawing see Table 14.
* Longitudinal.
** Transverse
*** Un-necked endurance bars

10a

Un-etched. × 100.

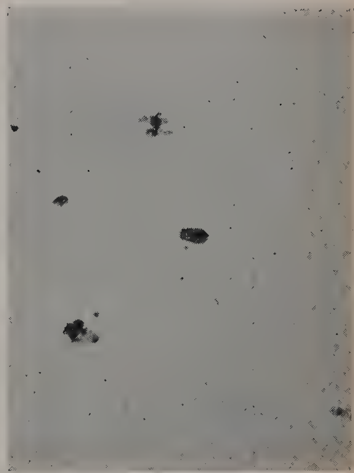
Section across direction of rolling, adjacent to fracture, showing inclusions in chromium-nickel steel No. 32.



10c

× 2.

Fracture of test-piece from chromium-nickel steel No. 32.



10b

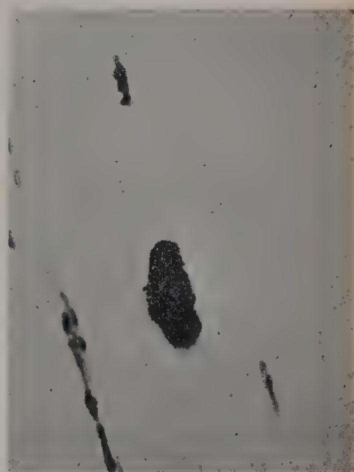
Un-etched. × 500.

Section across direction of rolling, adjacent to fracture, showing inclusions in chromium-nickel steel No. 32.

10d

Un-etched. × 100.

Section parallel to direction of rolling, adjacent to fracture, showing inclusions in chromium-nickel steel No. 32.

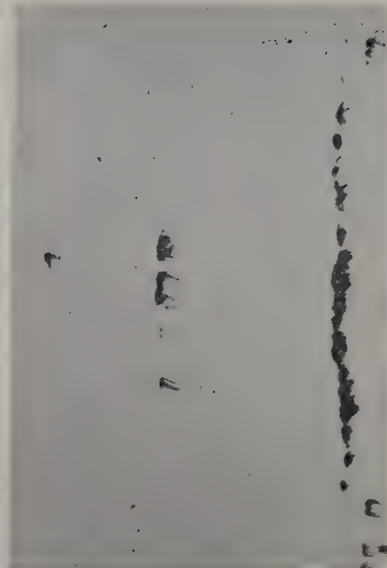


10e

Un-etched. × 500.

Section parallel to direction of rolling, adjacent to fracture, showing inclusions in chromium-nickel steel No. 32.

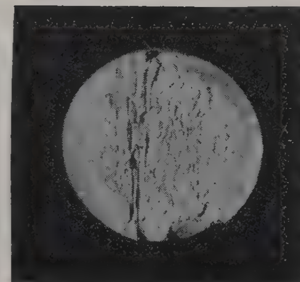
PLATE 10.—Fracture and inclusions, nickel-chromium steel No. 32. Transverse specimen.



11a

Un-etched. × 100.

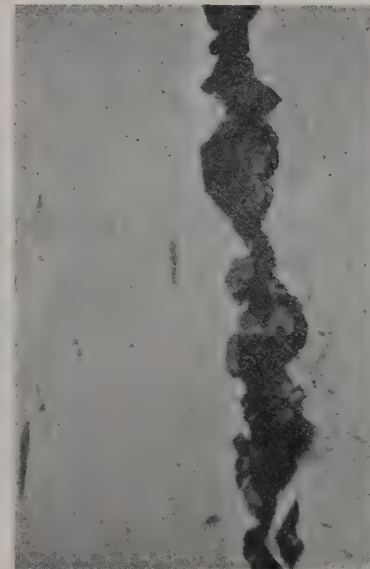
Section across direction of rolling, adjacent to fracture, showing inclusions in transverse tensile test-piece from chromium-nickel steel No. 32.



× 2.

11b

Fracture of transverse tensile test-piece from chromium-nickel steel No. 32.



11c

Un-etched. × 500.

Section across direction of rolling, adjacent to fracture, showing inclusions in transverse tensile test-piece from chromium-nickel steel No. 32.

Plate 11.—Fracture and inclusions, nickel-chromium steel No. 32. Another transverse specimen.

and plotted in Fig. 51. Duplicate specimens were tested. Closely agreeing values are averaged in the tables, discordant values are separately given and separately plotted.

"Longitudinal" means a specimen cut with its long axis parallel with the direction of rolling; "Transverse," one cut with its long axis across the direction of rolling. The proportional limit and yield point by extensometer are only slightly lower on transverse than on longitudinal specimens and the tensile strength is usually practically the same. The ductility of the transverse specimens is, however, very much lower than that of longitudinal ones, and the percentage of discrepancy is the greater the harder the steel.

All the longitudinal specimens, with the exception of those from steel No. 36, and from the 550° C. (1620° F.) draw of No. 28 (about 400 Brinell hardness) showed a star fracture or a serrated cup and cone fracture approaching a star. The transverse fractures ranged from silky part cup and cone fractures with no trace of lines to show the direction of rolling, to a flat, exceedingly woody fracture. In the 0.90 per cent. chromium series the plain chromium steel showed no lines, the stronger chromium-vanadium and low-molybdenum chromium steels showed faint lines, as did the high-molybdenum chromium steel, at the higher draw. This last steel showed a woody fracture at the lower draw which left it at around 400 Brinell hardness. The transverse Stanton specimens of all four steels showed similar fractures, lines being visible by which the direction of rolling could be recognized, but the fractures were not strongly woody.

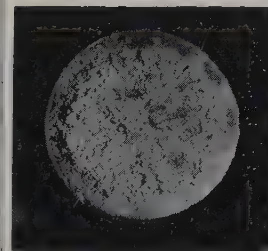
In the 2.50 per cent. Ni, 0.85 per cent. Cr series, all drawn to around 340 Brinell hardness, the plain chromium-nickel steel showed one slightly woody and one very woody transverse fracture, see Plates 10-c and 11-b. Two of the steels containing molybdenum gave transverse fractures that were not woody, (see Plate 12-b), while the other one containing molybdenum and the one containing vanadium gave slightly woody fractures. The one containing cerium gave irregular or laminated fractures, Plate 13-b, the sides of the specimen that had been nearest the surface in rolling showing a cup and cone fractures, and those that had been at the center showing a flat fracture. The fracture of these specimens containing cerium would scarcely be called woody. The fractures of the transverse endurance specimens of the chromium-nickel series of plates showed a slightly woody structure in all cases except in that of the steel containing cerium.

That the extreme woodiness of one transverse specimen of the plain chromium-nickel steel, No. 32, which gave an elongation of 1 per cent. and a reduction of area of 5 per cent., is directly traceable to large inclusions is shown by Plate 11-a, c, showing at 100 and 500 diameters a huge inclusion. This large lenticular inclusion is the direct cause of the deepest line

12a

Un-etched. × 100.

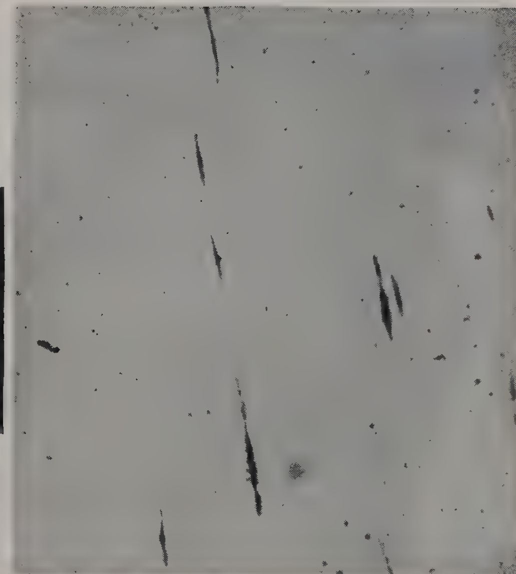
Section parallel to direction of rolling, adjacent to fracture, showing inclusions in nickel-chromium-molybdenum steel No. 34.



12b

× 2.

Fracture of transverse tensile test-piece from nickel-chromium-molybdenum steel No. 34.

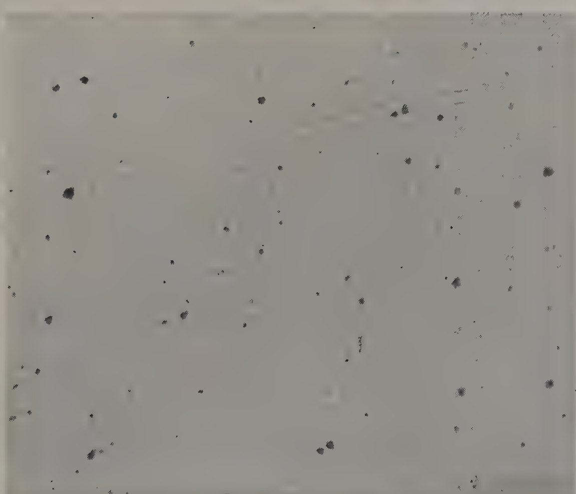


12c

Un-etched. × 500.

Section parallel to direction of rolling, adjacent to fracture, showing inclusions in nickel-chromium-molybdenum steel No. 34.

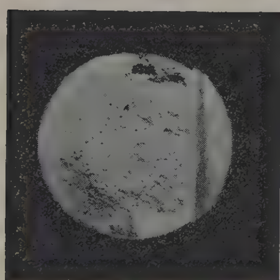
Plate 12.—Fracture and inclusions, nickel-chromium-molybdenum steel No. 34. Transverse specimen.



13a

Un-etched. × 100.

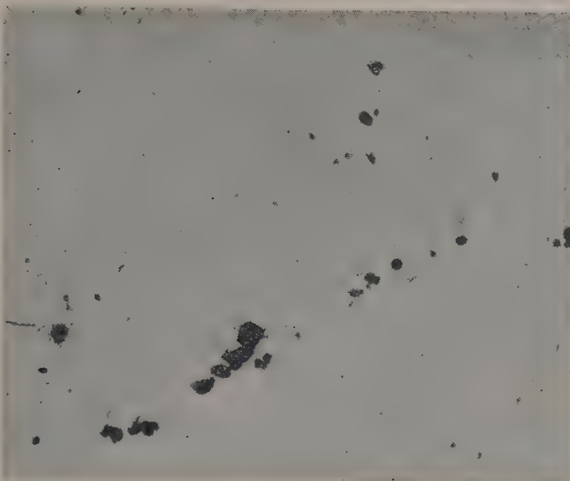
Section across direction of rolling, showing inclusions in nickel-chromium-cerium steel No. 36.



13b

× 2.

Fracture of test-piece from nickel-chromium-cerium steel No. 36.



13c

Un-etched. × 500.

Section parallel to direction of rolling, showing inclusions in nickel-chromium-cerium steel No. 36.

PLATE 13.—Fracture and inclusions, nickel-chromium-cerium steel No. 36. Transverse specimen.

shown on the fracture. By grinding back it was found that this inclusion extended up to the deepest line on the fracture.

The slightly woody structure of the other transverse specimen of steel No. 32, Plate 10-c, may be due to similar but smaller inclusions as shown in Plate 10-a-b, across the direction of rolling and Plate 10-d-e, parallel to direction of rolling.

That chromium-nickel-molybdenum steel No. 34 did not show a woody fracture in the tensile specimen but did usually show a slightly woody fracture on the endurance specimens may be due to the fact that, as shown by Plate 12-a-c, it was less dirty. Nevertheless, it was far from clean, and as shown by Plate 12-c at 500 diameters, the inclusions elongate in the direction of rolling.

Knowing the propensity of steels containing cerium to be dirty and seamy, and noting the evident connection between inclusions, low transverse ductility, and woodiness on transverse fracture, it is surprising to find that cerium steel No. 36, although showing laminated fractures, Plate 13-b, did not give woody fractures on tensile or endurance specimens. Microscopic examination reveals the expected dirtiness, see Plate 13-a-c.

Plate 13-c shows at 500 diameters, a surface on a plate along the direction of rolling. It will be noted that while the inclusions are grouped in lines in the direction of rolling, the individual inclusions are not elongated. The same thing is shown in Plate 8-c at 100 diameters of another cerium steel, also in the direction of rolling. It would appear that inclusions alone need not produce woodiness in a transverse specimen, even though they seem to be responsible for decreased transverse ductility.

In the case of steel No. 36 the more or less round inclusions decrease the ductility in both longitudinal and transverse specimens without woodiness being shown.

In the other plates of the group the inclusions are elongated and produce no woodiness in longitudinal, tensile or endurance specimens, and the longitudinal ductility is practically the same as that (tested longitudinally on rods) of the steels of similar composition in group E.

On transverse specimens the plates containing elongated inclusions all lose ductility and while the tensile specimens show only an approach to woodiness unless the inclusions are very large, the endurance specimens all show some woodiness.

Elongated inclusions therefore seem to favor the development of a woody transverse fracture. Weigand and Braendle (181-182) state that the "grain" effect in rubber, that is, the difference in properties of specimens tested with and across the direction of calendering is much more marked when the rubber is compounded with a substance like calcium sulfate, having acicular crystals, than when compounded with materials that are of

approximately the same dimensions in all directions. They state that "search for the ideal rubber pigment should include a study of the grain effects after cure in terms of not only size but crystal habit of the particles."

The Stanton figures on the longitudinal specimens, as shown by Fig. 30, (p. 141), agree with those on specimens from rolled bars with the exception of steel No. 28 at the low draw. The transverse specimens give lower Stanton values.

The longitudinal Izod specimens lie on or slightly under the curve of Fig. 31, (p. 142), drawn for tests on rods, while the transverse tests all lie far under the curve.

In the transverse tests the low Stanton and Izod figures are most probably due to the effect of inclusions.

In making Stanton tests on these plate specimens the orientation of the specimen was noted, half the specimens being placed so that point of impact of the hammer was in line with the direction of rolling, and the other half so that it was across this direction.

The orientation was similarly noted in the Izod tests but in neither case did the orientation show any effect, the various Stanton and Izod figures on each steel being good checks whatever the orientation. In the table the figures are averaged.

Although these chromium-nickel steels were furnace-cooled after the draw none of them show any temper-brittleness, whether or not they also contain molybdenum or vanadium, all of the longitudinal Izod tests agreeing well with Aitchison's curve for Izod vs. tensile strength.[10, p. 196] The longitudinal Izod tests from these plates were, however, not as good as those from the rods of Group E, or similar composition. The difference between the rod tests air-cooled after the draw and the longitudinal plate tests, furnace-cooled after the draw, is not sufficient to indicate temper brittleness.

Since the chromium-nickel and chromium-nickel-vanadium steels did not show temper-brittleness, all that can be said as to the effect of the addition of molybdenum is that such addition did not induce temper-brittleness, although had more chromium been added in place of the molybdenum, it is quite possible that temper-brittleness might have developed.

Endurance Tests on Plates

The 0.90 per cent. chromium series of plates in Group D was not given endurance tests on necked specimens. The fruitless testing of unnecked specimens (see Appendix B) had used up most of the stock without showing up the difference that certainly exists among steels varying in strength and hardness as these do. Most of the remaining stock was used in rise-of-temperature tests which likewise gave no useful data.

Necked-specimen endurance tests were, however, made on longitudinal and transverse specimens of the chromium-nickel plate series. These are of particular interest because the tensile strength and hardness of longitudinal and transverse specimens do not appreciably differ.

Moore and Jasper (172) concluded that "for wrought ferrous metals there is a fair degree of correlation between endurance limit and Brinell hardness." If this holds without qualification, the endurance limits of longitudinal and transverse specimens would therefore be expected to be the same. Aitchison and Barclay (183) state that the differences in longitudinal and transverse properties are probably of greater importance under static loading than under repeated stress.

TABLE 14

	No.	Direction	Original Draw Brinell Hardness	Original Draw Endurance Limit	Re-Draw Brinell Hardness	Re-Draw Endurance Limit	Notes
Ni, Cr	32	Long.	350	85,000	320	88,000	q, c
	32	Transv.	345	70,000	...	not re-drawn	
Ni, Cr, Mo	34	Long.	320	69,000 (a)	295	83,000	q, d
	34	Transv.	320	65,000 (a)	295	78,000	q
					295	78,000	s, e
Ni, Cr, Mo	37	Long.	330	67,000	300	89,000	q, e
	37	Transv.	310	58,000	300	70,000	q
					295	70,000	s, e
Ni, Cr, Mo	33	Long.	335	72,000	300	84,000	q, b
	33	Transv.	340	56,000	295	71,000	q, d
Ni, Cr, V	35	Long.	320	71,000 (b)	300	81,000	q
					300	89,000	s, g
	35	Transv.	320	60,000 (b)	300	75,000	q
					300	80,000	s, g
Ni, Cr, Ce	36	Long.	340	80,000	...	not re-drawn	
	36	Transv.	330	60,000 to 75,000	...	not re-drawn	

(q) quenched; (s) slow-cooled after draw.

(a) No. 34 treated 805° C. (1480° F.) oil, drawn 600° C. (1110° F.), Brinell hardness 365; re-drawn 625° C. (1155° F.).
(b) No. 35 treated 805° C. (1480° F.) oil, drawn 560° C. (1040° F.), Brinell hardness 300; re-treated 805° C. (1480° F.) oil, drawn 540° C. (1000° F.).
(c) No. 32-L re-drawn 450-475° C. (840-885° F.), then water quenched.
(d) No. 33-T and 34-L re-drawn by heating to 550° C. (1020° F.) in 1½ hours, then to 660° C. (1110° F.) in next 1½ hours, then water-quenched.
(e) See text.
(f) No. 33-L re-drawn at 600° C. (1110° F.) for about 2 hours.
(g) No. 35-L and 35-T brought up to 525° C. (975° F.) in 2½ hours.

McAdam,(47) however, compared longitudinal and tangential (*i.e.*, transverse) bars on two failed propeller shafts and found in one case an endurance limit of 44,500 pounds per square inch on longitudinal specimens and about 35,000 pounds per square inch on tangential specimens; and 41,000 pounds per square inch on longitudinal specimens and about 31,000 pounds on tangential specimens in the other. He says that non-metallic inclusions in steel have a decided effect in lowering the endurance ratio; that the endurance limits of specimens taken in a transverse direction

are usually considerably lower than those of longitudinal specimens; and that it is probable that inferiority of the transverse endurance ratio is due to the unfavorable orientation of inclusions in the transverse specimen and that this indicates that inclusions in steel have a noticeable effect.

The results of the endurance tests on transverse and longitudinal specimens are given in Table 14. The original tests will first be considered.

Inasmuch as the Upton-Lewis test stresses to a maximum two points on opposite sides of the specimen, it was thought that the orientation of these points, in respect to the direction of rolling, might have an effect. A rolled-out inclusion in a plate would have a lenticular form with the long axis in the direction of rolling. If a specimen with such inclusions is cut longitudinally with the direction of rolling, these lenticular inclusions will lie along the length of the specimen. If that specimen is bent, depending on how the specimen is oriented the bend may then come either across the sharp edges of the inclusion or across the flat sides. The latter case will occur when the neutral axis of the specimen is in the direction of rolling and this orientation was chosen for the longitudinal specimens after trials on steel No. 32-1 (Figs. 52 and 53) had shown no difference between this orientation and the one at 90 degrees to it.

In a specimen cut transversely to the direction of rolling the lenticular inclusions lie flat-wise as they did in the former case but the pointed ends lie crosswise of the specimen instead of along its length. After trials on 32-T (Fig. 52), in which the orientation with the neutral axis of the specimen in the Upton-Lewis machine was at 90 degrees to the direction of rolling, seemed to give lower results than the opposite one, this orientation for the transverse specimens was chosen as introducing the greatest disturbance due to inclusions.

The balance of the tests on plates were therefore made with the longitudinally cut specimens so placed that bending was against the flat sides of the lenticular inclusions (most favorable orientation), while the transversely cut specimens were bent against the sharp points of such inclusions (least favorable orientation).

The original tests on longitudinal specimens gave results for endurance limit, ranging from 65,000 to 72,000 pounds per square inch on the nickel-chromium-molybdenum and the nickel-chromium-vanadium, at Brinell hardness calling for 80,000 to 84,000 pounds per square inch on the basis of Moore's average and 69,500 to 73,500 pounds per square inch on the basis of his minimum. The chromium-nickel and the chromium-nickel-cerium steels showed a limit of 85,000 and 80,000 pounds at Brinell hardness calling for 87,500 to 85,000 pounds, average, or 78,000 to 74,500 pounds, minimum.

The transverse specimens showed limits of 56,000 to 71,000 pounds

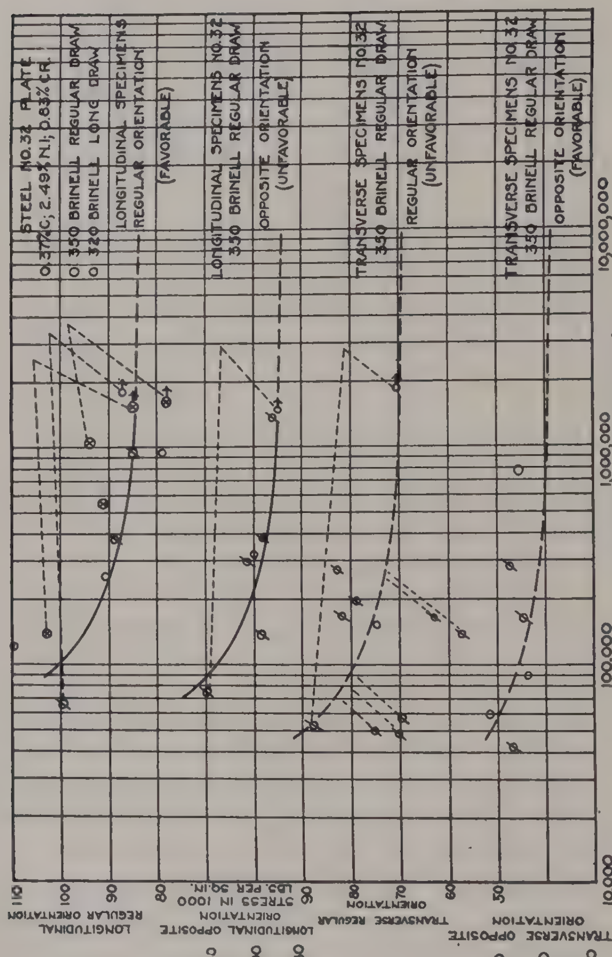


FIG. 52.—Endurance curves for longitudinal and transverse specimens cut from a plate of Ni-Cr steel.

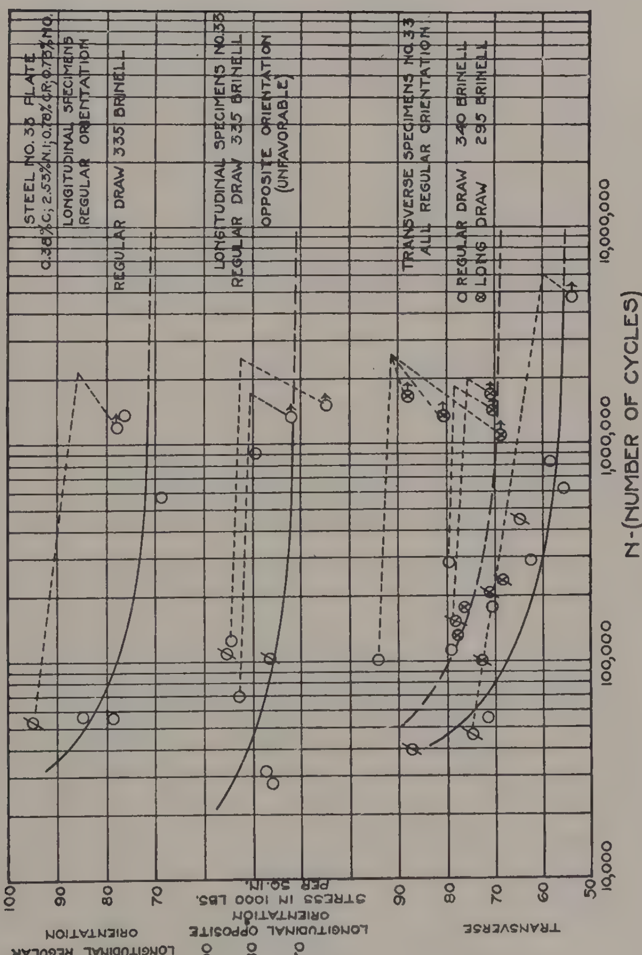


FIG. 53.—Endurance curves for longitudinal and transverse specimens cut from a plate of Ni-Cr-Mo steel.

when the S-N curve is located from the average of all points. Most of the steels, particularly the chromium-nickel, chromium-nickel-vanadium, and chromium-nickel-cerium, gave some points lying far below the average curve. The chromium-nickel steel No. 32-T (Fig. 52), for example, although indicating 71,000 pounds per square inch as the probable endurance limit, gave one specimen breaking at 140,000 cycles at only 55,000 pounds per square inch. All the steels showed individual points indicating that some individual transverse specimens of any of the steels would not have an endurance limit over the 56,000 to 58,000 pounds per square inch indicated by the averages for 33-T and 37-T.

The endurance tests on transverse specimens were far more erratic and the plots show a far wider "scatter" than was the case with specimens cut from rolled rod of steels of similar compositions.

All these plates in Group E were dirty, and one is tempted to ascribe the low values for transverse specimens as well as the irregularities in the tests, to the inclusions.

But, it was thought that internal stress from quenching, not sufficiently relieved in tempering, might also play a part, as was indicated by the tests on steels Nos. 22 and 26, Chapter 8. There was also the possibility that the slow cooling after the draw might introduce some factor analogous to the temper-brittleness sometimes found on Izod tests of such steels.

Again, plates rolled as these were are likely to have a more or less non-uniform, banded structure. Longer drawing times should tend to release stress and be conductive to uniformity of structure, while quenching after the draw should avoid trouble from temper-brittleness.

Nos. 33-T and 34-T were therefore re-drawn and quenched in water after the draw instead of being slow-cooled. On testing specimens so handled the endurance limit of No. 33-T increased from 56,000 to 71,000 pounds per square inch and of No. 34-L increased from 69,000 to 83,000 pounds per square inch (see Figs. 53 and 54) and the "scatter" of the plotted points was decreased.

Whenever enough specimens were available for another test the balance of the steels of this series were re-drawn. In some cases two sets of tests were made, one with a re-draw followed by a quench, the other with the re-draw followed by extremely slow cooling.

The balance of the S-N curves for these tests will not be given individually, but the results are tabulated under "second draw" Table 14, (p. 196), and in Fig. 55 are plotted the endurance limits found in these re-drawing tests as well as those on steel Nos. 22 and 26. The full line is the average curve from Fig. 32, the dashed line showing the usual maximum and minimum ranges of "scatter." The endurance limit at the original draw is plotted against the original-Brinell hardness and that point is connected

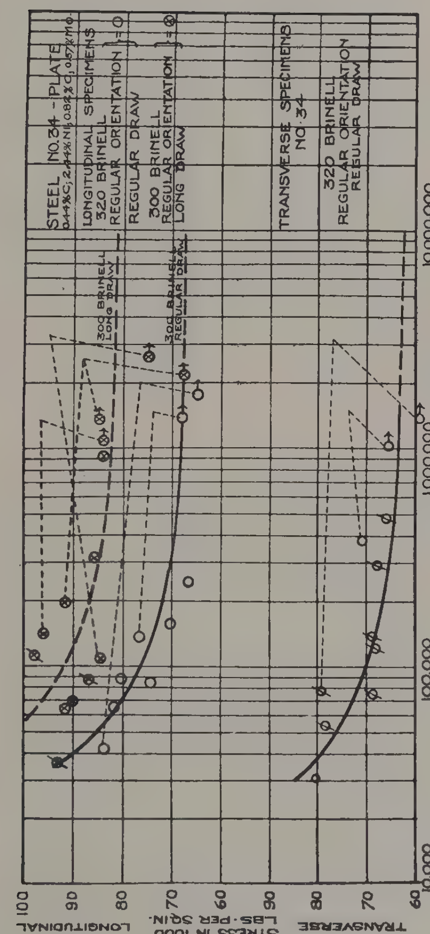


FIG. 54.—Endurance curves for longitudinal and transverse specimens cut from plate of Ni-Cr-Mo steel.

by a line bearing an arrow, with the point or points plotted for the endurance limit and Brinell hardness on re-drawing.

It is seen that although the original values after a one-hour draw were below the average, that re-drawing has brought them well above the average and in some cases, well above the ordinary high range of "scatter," and this in spite of a slight drop in Brinell hardness. Even were the endurance limit plotted for the original Brinell hardness the results would still be good. The endurance limit of the transverse specimens has been brought up above the original values for longitudinal bars.

The average of all the tests on the specimens cut from plates shows

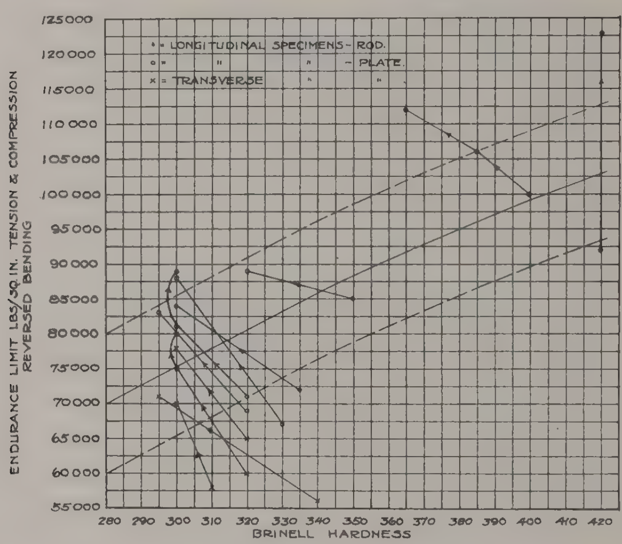
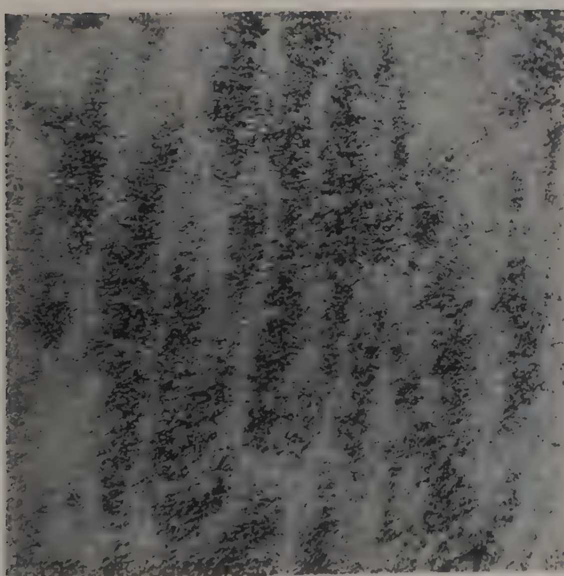


FIG. 55.—Effect of increasing the time of draw upon the endurance limit. The Brinell hardness is usually somewhat decreased, but the endurance limit rises instead of falling as would be expected from the softening.

that, while re-drawing caused a 9 per cent. decrease in Brinell hardness it caused a 12 per cent. increase in endurance limit.

It seems likely that the curvature of the plots of tensile strength (or Brinell hardness) against endurance limit (Fig. 32, Chapter 8) is due to the influence of internal quenching stresses, not relieved by the usual draw.

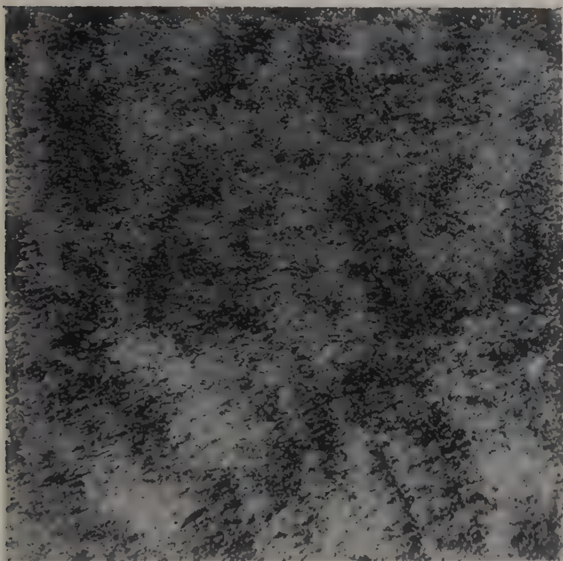
If this should be corroborated by the results of other investigators, it would appear that the way to make a spring which would have exceptional endurance properties would be to use a steel which can be drawn for a very long time at a very high temperature, in order to release the quenching stress, but which will still remain hard and strong and retain a high elastic limit. The property of resistance to tempering conferred by molybdenum should make this readily possible.



14a

Etchant: Stead's reagent. × 100.

Transverse specimen, original draw, chromium-nickel-molybdenum steel No. 33.



14b

Etchant: Stead's reagent. × 100.

Transverse specimen, redrawn, chromium-nickel-molybdenum steel No. 33.

PLATE 14.—Effect of re-draw on homogeneity of structure of steel No. 33.

Of course other factors than the release of stress may also play a part in the enhancement of the endurance limit. An increased homogeneity due to the prolonged draw would be expected. To search for this, bars of No. 33-T as originally drawn and tested, and after re-drawing, were examined after etching with Stead's reagent. Plate 14-a-b shows that the banded structure of the original draw is replaced on the longer draw by a more uniform structure. A similar effect was noted in the other steels.

The increased homogeneity afforded by a prolonged draw thus appears to accompany an increased endurance limit, and it is possible that this may be the prime factor instead of the release of quenching stresses. Both factors doubtless enter in, but the release of stress appeals to the authors as the more important. There is no indication that quenching after the draw in itself has any advantage over slow cooling, in respect to endurance.

The study of transverse specimens failed to show any justification for Cohade's statement (135) that molybdenum is the cause of poor transverse ductility. A molybdenum alloy steel is no worse in this respect because of its molybdenum content. Other alloy steels act like the molybdenum steel.

Poor transverse ductility, as a result of faulty steel-making, of faulty forging, or faulty heat-treatment is undoubtedly more marked in the strong alloy steels, such as can be made with the use of molybdenum, but the fault does not lie with the molybdenum.

Chapter 11.

Molybdenum, Cerium, and Zirconium in Nickel-Silicon Steels.

It has been shown that the alloying effect of molybdenum is exerted in a plain carbon steel and in the usual types of alloy steels. It is of interest to find out whether it has the same effect in less common types, especially since the point has been raised by Woodward (62, pp. 163, 268) that in one type,—high silicon nickel-silicon steel—the addition of molybdenum does not bring the ductility claimed for this element, and that some specimens of this steel which he tested at the Bureau of Standards were very brittle. This comment was based on his tests of nickel-silicon-molybdenum steels prepared by the authors in the course of a previous investigation. These steels are described and test results recorded in Table 15. The first four of the last five lines of the table give data from the Ford Motor Company on four experimental steels of this type with and without zirconium, while the last line gives data on a steel made in a 50-ton open-hearth furnace. The tests recorded in the last five lines were made on standard size test pieces, those made by the Bureau of Standards were on pieces of 2 inch gage length x 0.3 inch diameter. The latter test piece of course gives lower elongation than the standard piece.

These tests show the same effect on the normalized specimens, due to the air-hardening property conferred by molybdenum, as has been discussed in Chapter 9. In view of the great resistance to tempering of steels containing molybdenum, it seems likely that at higher draw temperatures the usual beneficial effect of molybdenum would have been found and that the occasional brittleness noted was due to the internal stress left by drawing at low temperature.

Johnson (126) has described nickel-silicon steels to which chromium, vanadium, molybdenum, tungsten, titanium, and zirconium have been added, but as he does not give the composition of the steels, little definite data can be gleaned from his article.

He states, however, that, for some purposes, the best steel was one containing molybdenum.

In co-operative work for the Navy Department the authors made up a series of nickel-silicon steels in which the effect of zirconium was studied to see if the results obtained by the Ford Motor Company could be duplicated. At the same time steels were made containing molybdenum

TABLE 15

C	Si	Mn	Ni	Mo	Ce	Zr	Normalized from ° C.	° F.	P. L.	Y. P.	T. S.	Elong.	R. A. Per Cent.
.40	1.45	.86	3.00	...	...	...	840	1545	......	107,500	141,500	11	30
.40	1.45	.84	3.10	...	...	...	840	1545	52,000	97,000	134,000	18.5	52
.49	1.30	.78	3.05	...	...	...	800	1470	53,000	92,500	129,000	21	53
.42	1.45	.83	3.25	.78(a)	...	...	780	1435	66,000	....	146,000	23	26
.44	1.50	.84	3.20	.77	...	...	780	1435	37,500	....	168,500	21	20
.42	1.30	.91	3.00	...	.19 .13	...	800	1470	......	142,500	158,500	5.5	17

(a) The Molybdenum steel showed only Ar″ on a cooling curve.

C	Si	Mn	Ni	Mo	Ce	Zr	Oil Quenched ° C.	° F.	Draw 3 Hours ° C.	° F.	P. L.	Y. P.	T. S.	Elong.	R. A. Per Cent.
.40	1.45	.86	3.00	...	...	...	840	1545	175	345	145,000	279,000	292,000	10.5	38.5
.40	1.45	.84	3.10	...	...	...	840	1545	175	345	165,000	204,500	286,000	8.5	39
.49	1.30	.78	3.05	...	...	...	800	1470	175	345	145,000	232,500	296,500	7.5	13
.42	1.45	.83	3.25	.78	...	...	780	1435	175	345	83,000	....	300,000	5.5	8.5
.44	1.50	.84	3.20	.77	...	...	780	1435	175	345	100,000	....	257,500	6.5	12
.42	1.30	.91	3.00	...	.19 .31	...	800	1470	175	345	83,000	289,000	325,000	5.5	11
.36	1.75	.61	2.86	...	...	...	845	1550	(b)	...	....	231,000	266,000	11.5	36
.36	1.25	.67	2.81	...	...	.20	845	1550	(b)	...	....	235,000	280,000	13	45.5
.45	1.21	.68	2.74	...	...	.35	845	1550	(b)	...	....	270,000	310,000	12.25	42
.45	1.65	.72	2.66	...	...	.54	845	1550	(b)	...	....	260,000	308,000	12	35
.46	1.43	.79	3.25	...	...	...	815	1500(c)	190	375(d)		290,000(e)	312,000	12	40

(b) Drawn to give 510-555 Brinell hardness.
(c) After previous normalizing from 870° C., (1600° F.), and oil-quenching from 845° C., (1550° F.).
(d) Drawn 1 hr.
(e) Elastic limit.

and cerium. The preparation of these steels has been described (as heats 1302-1333) in a previous publication.(63) They were made up in the electric furnace in a manner similar to the steels previously discussed and cast into 3 inch x 6 inch ingot molds. They were rolled to ¼ inch plate and heat-treated by the Halcomb Steel Company. Tensile and Izod specimens were cut from the plates and those tests and the Brinell determinations were made by Mr. Jerome Strauss of the Naval Gun Factory, whose data are given in Table 16. Publication of this data is permitted by the Navy Department.(269) Specimens from a few of the plates were returned to the authors for endurance testing.

The details of the composition, rolling, and methods of testing are given in Appendix C. Since the Izod tests had to be made on specimens smaller than the standard, the figures have been recalculated to the standard specimen. This is not strictly justifiable, but it gives figures certainly comparable among themselves and approximately comparable with results from standard specimens.

Since the tensile tests are on flat specimens, the elongation and reduction of area figures are again comparable among themselves, but only roughly comparable with results from standard specimens.

The steels were not cropped until after rolling so that the top or "A" plate may in some cases contain an undetected pipe. (The plate from the top of the ingot is given the letter A, the one next below it B, and so on). Three or four plates were made from each ingot.

There are several sets of variables in the composition of these steels. Steels I-1 to I-7 inclusive and I-31 have a silicon content under 2 per cent. The balance run between 2 per cent. and 2.75 per cent. silicon. The carbon content varies from 0.35 per cent. to 0.50 per cent. The nickel is approximately constant save in I-26 where 0.60 per cent. nickel was replaced by 0.60 per cent. copper. Manganese varies from 0.50 per cent. to 0.80 per cent. The variation in zirconium and cerium content should be noted. The top or "A" plate is higher in zirconium than the plate from the bottom. The intermediate plates would presumably have intermediate composition.

The chief variable in I-1 to I-7, and in I-8 to I-25 was the zirconium content. In I-26 to I-32 the effect of copper, vanadium, aluminum, molybdenum, and cerium was sought.

These plates were spread out by cross-rolling to twice the width of those described in Chapter 10, so that the longitudinal and transverse results would not be expected to show as much difference as those steels, which had no cross-rolling.

The composition, heat-treatment and tensile and Izod test results are summarized in Table 16. To distinguish these steels from those previously considered, the nickel-silicon steels have been designated by prefixing the letter I to the serial number. It is at once noted in Table 16

TABLE 16

Steel No.	Position	Direction	Composition: C	Si	Mn	Ni	Zr	Ti	Al	Heat Treatment: Oil Quenched from °C.	°F.	No. of draws	Final Draw Temp. °C.	°F.	(Flat Bars) Brinell Hardness[a]	Prop. Lim. lbs./sq. in.	Tensile Strength lbs./sq. in.	Elon. % in 2"	R. A. %	Fracture of Tensile Specimen	Computed Izod Value Ft. lbs. M.N.*** [a]	End. Limit Flat-Necked Specimen Reverse Bend lbs./sq. in.
I 1	C	L*	.46	1.42	.80	3.02			tr.	845	1550	1	345	650	555	247,000	281,000	2	5	Part cup	19	
I 1		T**														241,500	282,000	6½	24½	Part cup	14½	
I 1	B	L										3	480	900	420	183,000	203,000	11½	32	Part cup	12½	
I 1		T														186,000	204,000	7½	13½	Part cup	12	
I 1	A	L										2	525	975	365	160,000	178,000	10½	21	Cup	15	
I 1		T														159,000	178,000	12½	35	Sq. silky	11½	
I 2	C	L	.35	1.76	.56	2.93			tr	870	1600	2	345	650	510	187,000	245,000	5	15	Cup	20	
I 2		T														196,000	250,000	5½	24	Cup	16½	
I 2	D	L										2	370	700	460	195,000	235,500	5	25	Part cup	19	
I 2		T														206,500	245,500	11	35	Part cup	13½	
I 2	B	L										2	480	900	420	142,500	181,000	13	40½	Part cup	21½	
I 2		T														152,500	180,000	9	28½	Part cup	14	
I 2	A	L										2	540	1000	365	138,000	159,000	12½	28½	Ang. silky	29	
I 2		T														138,000	155,500	11½	20	Ang. silky	22	
I 3	C	L	.36	1.72	.46	2.94	.23	.02	tr.	845	1550	1	370	700	510	212,000	253,000	13	33	Part cup	25	
I 3		T														214,500	253,000	5	22½	Part cup	19	
I 3	A	L					.26					2	400	750	470	206,500	232,000	7½	36	Cup	17½	
I 3		T														212,000	237,500	5	11	Part cup	16	
I 3	B	L										3	455	850	420	171,500	193,000	10½	40½	Part cup	27½	
I 3		T														177,500	195,000	8½	25	Part cup	23	
I 4	D	L	.41	1.60	.65	2.97	.31	.01	.06	845	1550	2	400	750	505	209,000	248,500	8½	33	Cup	24	
I 4		T														209,500	249,500	5½	20½	Part cup	19½	
I 4	B	L										1	425	800	460	202,500	222,000	9	35½	Cup	24	
I 4		T														202,500	220,000	3½	12	Ang. silky	20½	
I 4	C	L										5	525	975	375	156,500	174,500	12	27	Square	20	
I 4		T														156,500	174,000	10	26	Cup	18	
I 4	A	L					.38					3	595	1100	310	123,500	148,000	13	31	Ang. silky	26	
I 4		T														128,500	152,000	11	25	Ang. silky	22	
I 5	B	L	.42	1.66	.63	2.97	[b]	.02	.19	845	1550	1	345	650	555	224,000	273,000	7	31½	Part cup	22½	
I 5		T														217,000	236,500	1	2	Part cup & laminat'd	20	
I 5	A	L					.45					2	400	750	505	224,000	254,500	6	28	Cup	18½	
I 5		T														223,000	247,000	1	4½	Part cup	17½	
I 5	C	L					.32					4	540	1000	365	150,000	173,000	12½	19½	Ang. lam.	14	
I 5		T														155,000	171,500	11½	24½	Ang. silky	14	

*, **, *** See notes at end of table.

[a] Brinell and Izod figures, average of 4 and 2 tests respectively.

[b] See A and C plates for Zr content.

TABLE 16 (Continued)

Steel No.	Position	Direction	Composition C	Si	Mn	Ni	Zr	Ti	Al	Heat Treatment Oil Quenched from °C.	°F.	No. of draws	Final Draw Temp. °C.	°F.	(Flat Bars) Brinell Hardness[a]	Prop. Lim. lbs./sq. in.	Tensile Strength lbs./sq. in.	Elon. % in 2"	R. A. %	Fracture of Tensile Specimen	Computed Izod Value Ft. lbs. M.N.***	End. Limit Flat-Necked Specimen Reverse Bend lbs./sq. in.
I 6	C	L	.36	1.90	.52	2.93	.38	.04	tr.	860	1575	1	345	650	510	188,500	241,500	6	21	Part cup	19½	
I 6		T														191,000	240,500	6	19½	Ang. silky	17	
I 6	A	L					.55					2	370	700	505	201,500	242,500	4	13	Ang. lam.	19	
I 6		T														200,000	243,000	2½	6	Ang. lam.	11½	
I 6	B	L										4	480	900	360	155,500	171,000	12½	33½	Part cup	21½	
I 6		T														140,500	166,500	6	7½	Part cup	20	
I 7	D	L	.36	1.80	.54	2.98	.38	.03	.02	860	1575	2	345	650	490	188,000	238,000	6½	31	Part cup	20½	
I 7		T														191,500	237,000	3½	12½	Part cup	20	
I 7	A	L					.61					1	400	750	475	201,000	229,500	6	23	Part cup, lam.	14	
I 7		T														200,000	228,500	7½	29	Part cup	20	
I 7	C	L										4	480	900	365	154,000	173,500	11	31½	Part cup	23	
I 7		T														158,500	175,500	10	29	Part cup	17	
I 7	B	L										4	565	1050	320	134,000	148,000	15	39	Ang. silky	25	
I 7		T														133,500	151,000	14½	35½	Ang. silky	21	
I 8	B	L	.46	2.33	.81	3.01			tr.	860	1575	1	480	900	445	198,000	217,500	3½	5½	Square	6½	
I 8		T														188,000	212,000	7	16	Part cup	7½	
I 8	C	L										6	540	1000	390	166,500	190,500	9½	14½	Sq. silky	7½	
I 8		T														159,500	189,500	7	11	Sq. silky	5½	
I 8	A	L										2	565	1050	370	151,500	177,000	10½	16	Ang. silky	4½	
I 8		T														157,000	167,000	2	4½	Sq. silky	4	
I 9	C	L	.41	2.47	.70	3.00			tr.	860	1575	2	415	775	505	211,500	254,000	8	31½	Part cup	21½	115,000±
I 9		T														224,500	246,000	1	4½	Ang. silky	19	95,000±
I 9	D	L										5	510	950	410	170,000	192,500	11	26	Ang. silky	6	90,000
I 9		T														169,500	192,000	10	20	Ang. silky	7	94,000
I 9	A	L										1	595	1100	360	145,500	169,500	14	26½	Ang. lam.	12	85,000
I 9		T														152,000	173,000	14½	29	Ang. lam.	7½	82,000
I 9	B	L										3	595	1100	345	148,000	164,500	14	28	Ang. silky	17	88,000
I 9		T														147,500	158,000	5	7	Ang. silky	17	82,000
I 10	D	L	.40	2.73	.57	2.95	.03	.01	.01	860	1575	1	400	750	520	226,500	269,500	8	32	Part cup	25½	110,000
I 10		T														218,000	268,000	5	6½	Part cup	17	100,000
I 10	C	L										5	540	1000	385	167,000	185,000	11½	21	Sq. silky	14½	85,000
I 10		T														161,000	182,000	10	13	Sq. silky	10	85,000±
I 10	B	L										3	595	1100	355	150,500	176,500	15	37	Sq. lam.	12	94,000
I 10		T														136,000	163,500	11½	15	Sq. lam.	17½	87,000
I 10	A	L					.04					1	595	1100	320	131,000	156,000	18	34	Ang. silky	17	85,000
I 10		T														139,500	161,500	17	34	Sq. silky	18½	87,000

TABLE 16 (Continued)

Steel No.	Position	Direction	Composition C	Si	Mn	Ni	Zr	Ti	Al	Heat Treatment: Oil Quenched from °C.	°F.	No. of draws	Final Draw Temp. °C.	°F.	(Flat Bars) Brinell Hardness[a]	Prop. Lim. lbs./sq. in.	Tensile Strength lbs./sq. in.	Elon. % in 2"	R. A. %	Fracture of Tensile Specimen	Computed Izod Value Ft. lbs. M.N.***	End. Limit Flat-Necked Specimen Reverse Bend lbs./sq. in.
I 11	D	L	.39	2.46	.70	3.00	.11	.02	tr.	860	1575	2	415	775	475	203,500	237,000	8½	37½	Part cup	22½	
I 11		T														202,500	226,000	7	14	Part cup	19	
I 11	C	L										2	510	950	405	164,500	189,500	11½	31½	Ang. silky	7	
I 11		T														168,500	190,000	9½	23	Ang. silky	11½	
I 11	B	L										2	540	1000	375	157,000	179,000	11	25	Ang. silky	8½	
I 11		T														154,500	175,000	11½	25½	Ang. silky	4	
I 11	A	L					.12					3	610	1125	320	133,500	155,000	17½	38½	Ang. silky	23½	
I 11		T														131,000	150,000	15½	38	Sq. silky	26½	
I 12	D	L	.47	2.31	.70	2.89	.11	.01	.02	860	1575	2	425	800	510	194,000	255,500	2	3½	Part cup	14	
I 12		T														219,500	258,500	7	24½	Part cup	12½	
I 12	C	L										2	510	950	430	179,500	205,000	8½	18	Sq. laminated	8½	
I 12		T														182,000	206,000	10½	26½	Sq. silky	3½	
I 12	B	L										4	595	1100	340	133,500	162,000	13½	32	Ang. silky	15½	
I 12		T														132,000	163,000	15	26½	Sq. silky	9½	
I 12	A	L					.11					2	610	1125	335	133,000	159,000	17½	38½	Ang. silky	22	
I 12		T														140,000	164,000	12½	19½	Sq. silky	8½	
I 13	C	L	.50	2.25	.72	2.92	.12	.02	tr.	860	1575	1	415	775	545	227,500	277,500	7½	32½	Part cup	15½	
I 13		T														231,500	278,000	5½	23½	Part cup	16½	
I 13	B	L										4	540	1000	420	169,500	197,000	11	25	Ang. silky	4½	
I 13		T														171,000	199,000	9½	16½	Ang. silky	4	
I 13	A	L					.12					3	595	1100	370	152,000	179,000	12	23	Ang. silky	4½	
I 13		T														144,000	171,500	10½	13½	Sq. silky	5½	
I 14	D	L	.46	2.45	.72	3.04	.21	.03	tr.	860	1575	3	480	900	445	191,000	212,500	10	26½	Part cup	6	
I 14		T														192,500	211,500	7½	18½	Part cup	8	
I 14	C	L										5	510	950	420	177,000	200,000	11	24	Ang. silky	5½	
I 14		T														178,500	201,000	8	14	Sq. silky	4	
I 14	A	L					.21			{reque 860–1	nched 575		595 then 565	1100 then 1050}	385	162,000	185,000	11½	28	Ang. silky	6	
I 14		T														146,500	154,000	1	1	Laminated-split	3	
I 14	B	L										3	595	1100	350	149,000	171,500	16	33	Sq. silky	12	
I 14		T														146,000	168,000	12½	24½	Sq. silky	12	
I 15	D	L	.41	2.66	.64	2.95	.17	.01	.08	860	1575	1	400	750	515	219,000	259,500	3½	6½	Part cup	24	
I 15		T														221,500	266,500	5	19½	Part cup	20½	
I 15	C	L										2	565	1050	405	165,000	191,000	11	29	Ang. silky	5	
I 15		T														162,000	183,500	8	21	Ang. silky	3½	

TABLE 16 (Continued)

Steel No.	Position	Direction	Composition: C	Si	Mn	Ni	Zr	Ti	Al	Heat Treatment: Oil Quenched from °C.	°F.	No. of draws	Final Draw Temp. °C.	°F.	(Flat Bars): Brinell Hardness[a]	Prop. Lim. lbs./sq. in.	Tensile Strength lbs./sq. in.	Elon. % in 2"	R. A. %	Fracture of Tensile Specimen	Computed Izod Value Ft. lbs. M.N.*** [a]	End. Lim Flat-Necked Specimen Reverse Bend lbs./sq. in.
I 15	B	L	*									4	540	1000	365	152,500	177,500	11½	27	Ang. silky	5	
I 15		T														154,000	177,500	9½	15	Ang. silky	3	
I 15	A	L					.24					1	595	1100	320	138,000	158,000	8	9	Ang. laminated	10½	
I 15		T														128,000	151,000	9	11½	Ang. laminated	10½	
I 16	B	L	.43	2.40	.57	3.00	a	.03	tr.	860	1575	1	370	700	510	219,500	281,500	7½	31½	Part cup	22½	109,000
I 16		T														224,000	284,500	4	10	Part cup	16	100,000
I 16	C	L					.22					5	510	950	420	153,000	199,000	11	22½	Part cup	10	.... or less
I 16		T														173,000	198,000	11	23½	Part cup laminated	4	
I 16	A	L					.26					4	595	1100	345	143,000	166,000	13½	34	Ang. silky	20½	
I 16		T														141,500	162,000	15	34½	Ang. silky	8	
I 17	D	L	.43	2.45	.72	2.84	.26	.02	.12	860	1575	1	415	775	510	205,500	258,000	8	35	Part cup	17½	
I 17		T														215,500	259,000	2½	5	Part cup	16	
I 17	C	L										1	455	850	465	195,500	221,500	8½	24½	Ang. silky	14	
I 17		T														195,000	223,000	8½	28½	Part cup	12	
I 17	B	L										3	540	1000	385	164,500	185,000	11	30	Ang. silky	5½	
I 17		T														164,500	186,000	7	10½	Sq. silky	5	
I 17	A	L					.45					2	610	1125	330	133,000	156,000	16	35½	Ang. silky	13	
I 17		T														138,000	161,000	14½	30½	Sq. silky	13	
I 18	A	L	.36	2.54	.64	2.94	.40	.02	.02	870	1600	1	400	750	505	200,000	251,000	8	28½	Part cup	13½	
I 18		T														204,500	245,000	3½	12½	Ang. laminated	15	
I 18	C	L										3	480	900	420	178,500	199,000	10	35½	Part cup	9½	
I 18		T														179,500	200,500	10	30	Part cup	8½	
I 18	B	L										2	540	1000	365	149,000	171,000	14½	36½	Ang. silky	12	
I 18		T														151,000	171,500	13	32	Sq. silky	10	
I 18	D	L					.25					1	595	1100	335	135,000	158,000	14½	34	Ang. silky	19	
I 18		T														135,000	155,000	14	28	Ang. silky	17	
I 19	A	L	.41	2.13	.57	3.07	.55	.03	.01	860	1575	2	425	800	475	199,000	225,000	4	9	Part cup	15	
I 19		T														209,500	230,000	7	23	Part cup	13	
I 19	B	L										2	480	900	420	174,500	198,500	10½	34½	Part cup	17½	
I 19		T														183,500	199,000	10½	30	Part cup	12½	
I 19	C	L					.33					2	540	1000	365	144,000	170,500	12	31½	Sq. silky	8½	
I 19		T														148,000	172,000	12	24	Ang. silky	10	
I 20	B	L	.40	2.48	.63	3.05	b	.04	.02	860	1575	1	345	650	520	211,500	264,500	6	19	Part cup	21	
I 20		T														209,000	258,000	3	5	Part cup	16½	
I 20	C	L										1	495	925	410	167,000	191,000	9½	30½	Sq. silky	16	

* See preceding page for composition and heat treatment.
[a] See A and C plates for Zr content.
[b] See A and D plates, next page, for Zr content.

TABLE 16 (Continued)

Steel No.	Position	Direction	Composition C	Si	Mn	Ni	Zr	Ti	Al	Heat Treatment: Oil Quenched from °C.	°F.	No. of draws	Final Draw Temp. °C.	°F.	(Flat Bars) Brinell Hardness[a]	Prop. Lim. lbs./sq. in.	Tensile Strength lbs./sq. in.	Elon. % in 2"	R. A. %	Fracture of Tensile Specimen	Computed Izod Value Ft. lbs. M.N.***	End. Limit Flat-Necked Specimen Reverse Bend lbs./sq. in.
I 20	C	T	*													168,500	188,500	6	12½	Sq. silky	7½	......
I 20	D	L					.50					5	510	950	385	149,000	183,000	10	23	Part cup laminated	15	......
I 20		T														169,000	184,000	10	21	Part cup	10½	......
I 20	A	L					.65					1	595	1100	325	134,000	152,500	10½	15	Sq. silky	14½	......
I 20		T														129,500	148,500	13½	20½	Sq. silky	15½	......
I 21	C	L	.39	2.38	.62	2.94	.40	.07	tr.	870	1600	2	345	650	505	202,000	253,500	7	28½	Cup	25	......
I 21		T														208,000	254,000	4	16½	Part cup	17½	......
I 21	A	L					.50					2	400	750	505	204,000	243,500	3½	9½	Ang. laminated	26	......
I 21		T														209,000	247,000	6½	23½	Ang. laminated	18	......
I 21	B	L										3	480	900	400	170,000	189,000	11	30	Part cup	25	......
I 21		T														174,000	189,500	6	9	Sq. silky	17½	......
I 22	A	L	.42	2.46	.64	2.98	.55	.05	tr.	860	1575	1	400	750	520	221,000	263,000	7	28½	Cup	23	......
I 22		T														231,000	266,000	5½	23½	Part cup	21½	......
I 22	B	L										4	510	950	420	166,500	193,500	10	28	Sq. silky	11	......
I 22		T														167,500	193,000	2	4	Aq. silky	9½	......
I 22	C	L					.35					2	540	1000	385	164,500	164,500	½	3	Sq. laminated	13	......
I 22		T														165,000	180,500	7½	11	Sq. silky	6½	......
I 23	A	L	.36	2.68	.64	2.96	.65	.09	tr.	860	1575	1	205	400	485	180,000	244,000	6	15½	Part cup	15	......
I 23		T														152,500	227,000	4½	10	Sq. silky	18	......
I 23	C	L										1	205	400	465	153,000	231,000	7	11½	Ang. laminated	22½	......
I 23		T														151,000	216,000	6½	14	Ang. laminated	18½	......
I 23	D	L					.45					2	480	900	385	139,500	179,500	11½	35½	Part cup	16	......
I 23		T														149,000	185,000	8	19	Part cup	9½	......
I 23	B	L										2	540	1000	350	135,500	161,500	4	8½	Sq. silky	11½	......
I 23		T														128,000	159,000	9½	14	Sq. silky	10½	......
I 24	D	L	.42	2.75	.63	2.97	.45	.07	tr.	870	1600	1	400	750	500	209,000	241,000	6	30½	Part cup	17	......
I 24		T														197,500	240,000	4½	16½	Ang. silky	15	......
I 24	C	L										3	480	900	420	182,500	193,500	10½	27½	Part cup	14½	......
I 24		T														182,500	193,000	2	7	Ang. silky	15	......
I 24	B	L										2	540	1000	375	147,000	170,000	7½	16	Part cup	16½	......
I 24		T														158,000	172,000	6	8½	Sq silky	14	......
I 24	A	L					.70					1	595	1100	330	138,000	151,000	11½	19	Ang. silky	15½	......
I 24		T														141,000	150,500	2	7	Ang. silky	9	......
I 25	B	L	.43	2.04	.58	2.96	.60	.05	.04	860	1575	1	455	850	430	197,000	214,000	8	26	Part cup	12	......
I 25		T														137,000	197,500	6	11	Sq. silky	11	......

* See preceding page for composition and heat-treatment.

TABLE 16 (Continued)

Steel No.	Position	Direction	Composition: C	Si	Mn	Ni	Zr	Ti	Al	Heat Treatment: Oil Quenched from °C.	°F.	No. of draws	Final Draw Temp. °C.	°F.	(Flat Bars): Brinell Hardness[a]	Prop. Lim. lbs./sq. in.	Tensile Strength lbs./sq. in.	Elon. % in 2"	R. A. %	Fracture of Tensile Specimen	Computed Izod Value Ft. lbs. M.N.***	End. Limit Flat-Necked Specimen Reverse Bend lbs./sq. in.
I 25	A	L	*				.90					4	540	1000	385	163,500	180,000	12	30½	Ang. silky	11	
I 25		T														163,000	179.000	11	27	Ang. silky	9	
I 26	D	L	.39	2.56	.50	2.40	.60	Copper		860	1575	1	345	650	515	205,000	257,500	6½	22½	Part cup	25	
I 26		T														218,000	274,500	1½	4	Part cup	19½	
I 26	C	L										4	510	950	420	179,000	184,000	11½	33	Ang. silky	8	
I 26		T														172,000	193,000	5	7½	Sq. silky	8	
I 26	B	L										1	595	1100	385	163,500	184,500	11½	28½	Ang. silky	10½	
I 26		T														141,000	164,500	10	18½	Sq. silky	9	
I 26	A	L										2	620	1150	325	132,500	154,000	15½	42	Ang. silky	16½	
I 26		T														134,000	157,500	16	32½	Ang. silky	12½	
I 27			.46	2.42	.70	2.92	.37	Uranium		Broke in rolls												
I 28	A	L	.36	2.42	.51	2.94	.12	Vanadium		870	1600	1	400	750	520	224,000	262,500	7	19½	Ang. laminated	22	100,000
I 28		T														219,500	254,000	5	16	Ang. silky	17	
I 28	B	L										4	510	950	425	181,000	206,000	9	21	Ang. silky	14	105,000
I 28		T														184,500	204,500	9	22	Ang. silky	7½	
I 28	C	L										3	610	1125	390	158,000	184,000	11½	25½	Ang. silky	13	96,000
I 28		T														162,500	180,000	6	7	Sq. silky	10	
I 29	A	L	.43	2.00	.50	2.94	.20	Aluminum		860	1575	1	400	750	520	213,000	265,000	6	26½	Part cup	20½	
I 29		T														218,500	268,000	5½	24	Part cup	17	
I 29	B	L										3	480	900	435	178,000	203,000	5½	16	Part cup	16½	
I 29		T														186,000	209,000	7	18	Part cup	12	
I 29	C	L										1	510	950	365	146,500	186,000	8½	17	Ang. silky	9½	
I 29		T														116,000	145,500	12½	26½	Ang. silky	18	
I 30	D	L	.37	2.50	.52	2.95	.70	Molybdenum		860	1575	1	400	750	515	227,000	275,000	7	34	Part cup	21	
I 30		T														228,500	272,500	6	22	Part cup	15	100,000±
I 30	C	L										6	595	1100	385	163,500	185,500	7	29	Sq. silky	17½	92,000
I 30		T														166,000	191,000	6	8½	Ang. silky	12½	
I 30	B	L										3	620	1150	340	145.500	176,000	12	28	Ang. laminated	8½	92,000
I 30		T														140,000	167,000	11½	22½	Ang. laminated	15½	
I 30	A	L										2	620	1150	340	146,500	171,000	15	37	Ang. silky	26	92,000±
I 30		T														138,500	160,000	15	29	Ang. laminated	19	
I 31	D	L	.43	1.77	.78	2.78	.22	Cerium		860	1575	1	400	750	510	206,500	256,000	8½	36	Part cup	28	
I 31		T						c								210,500	259,000	2½	8½	Part cup	23	
I 31	C	L										4	480	900	420	173,000	195,000	10	27½	Part cup	19½	

* See preceding page for composition and heat-treatment.

[c] See next page for Cerium content of A Plate.

TABLE 16 (Continued)

Steel No.	Position	Direction	Composition: C	Si	Mn	Ni	Zr	Ti	Al	Heat Treatment: Oil Quenched from °C.	°F.	No. of draws	Final Draw Temp. °C.	°F.	Brinell Hardness[a]	(Flat Bars) Prop. Lim. lbs./sq. in.	Tensile Strength lbs./sq. in.	Elon. % in 2"	R. A. %	Fracture of Tensile Specimen	Computed Izod Value Ft. lbs. M.N.***	End. Limit Flat-Necked Specimen Reverse Bend lbs./sq. in.
I 31	C	T	d	......	......	......	......	......	......	......	......	......	......	......	......	171,500	195,000	4½	8½	Part cup	18	....
I 31	A	L	......	......	......	......	.54	Ceri	um	......	......	1	510	950	380	152,500	180,500	12	32½	Ang. silky	20½	....
I 31		T	......	......	......	......	......	......	......	......	......	......	......	......	......	149,000	176,500	4	6½	Ang. silky & granular	13½	....
I 31	B	L	......	......	......	......	......	......	......	......	......	4	595	1100	325	128,000	154,000	17	43	Ang. silky & granular	22½	....
I 31		T	......	......	......	......	......	......	......	......	......	......	......	......	......	130,000	154,000	13	30	Ang. silky	20	....
I 32	C	L	.43	2.54	.91	2.86	c	Ceri	um	860	1575	3	425	800	510	200,000	242,000	1½	4	Part cup	17½	96,000±
I 32		T	......	......	......	......	......	......	......	......	......	......	......	......	......	212,500	255,000	6	20½	Part cup	11½	94,000±
I 32	D	L	......	......	......	......	.33	Ceri	um	......	......	3	455	850	405	149,000	199,000	8	10	Sq. silky	8	83,000
I 32		T	......	......	......	......	......	......	......	......	......	......	......	......	......	158,000	185,500	2½	4½	Sq. granular	10½	75,000
I 32	B	L	......	......	......	......	......	......	......	......	......	3	595	1100	350	142,000	167,000	11	24	Sq. silky	16	77,000
I 32		T	......	......	......	......	......	......	......	......	......	......	......	......	......	142,000	169,000	11½	12½	Sq. silky	16	75,000±
I 32	A	L	......	......	......	......	.58	Ceri	um	......	......	1	595	1100	330	137,000	160,500	6½	10	Ang. silky	22½	68,000±
I 32		T	......	......	......	......	......	......	......	......	......	......	......	......	......	130,500	156,000	6	7½	Sq. silky	10	75,000±

* Longitudinal.
** Transverse.
*** Mesnager Notch. Izod—average of 2.
[a] Brinell—average of 4.
[b] Zirconium content of the top of the ingot is put in the line for the A Plate.
Zirconium content of the bottom of the ingot is put in the line for the C or D Plate (C if 3, and D if 4 plates were made from the ingot).
[c] Same for Cerium content.
[d] See preceding page for composition and heat-treatment.

that the proportional limit and tensile strength figures, (with the exception of I-22 to I-24, the steels highest in zirconium, where the results are erratic) show practically no variation between longitudinal and transverse figures and that the Izod figures show somewhat higher values for the longitudinal tests, but these are all quite erratic.

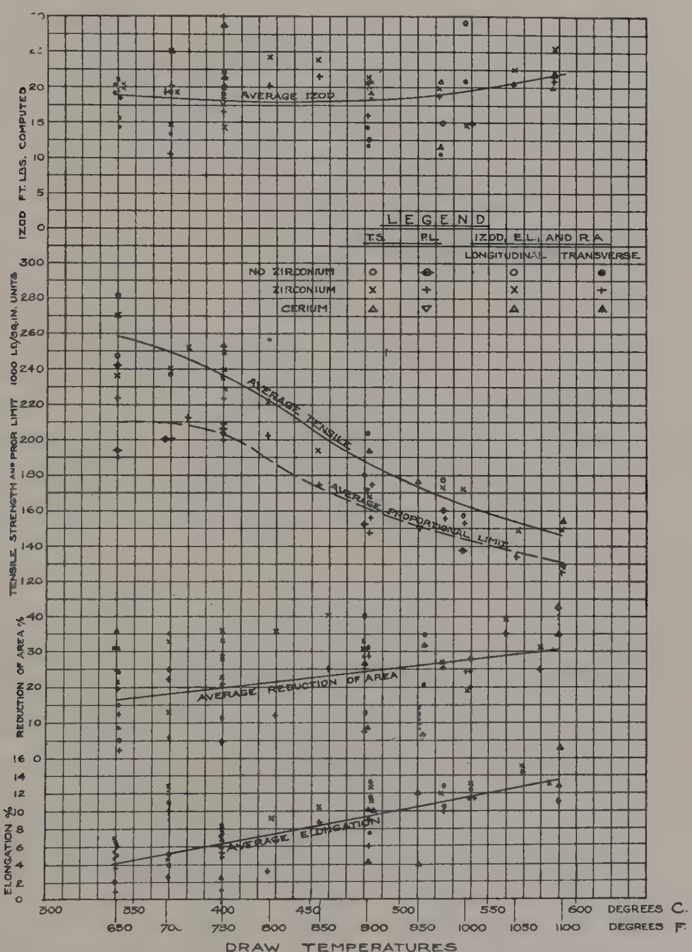


FIG. 56.—Plot of properties of Ni-Si, Ni-Si-Zr and Ni-Si-Ce steels.

In Fig. 56 have been plotted the average of the longitudinal and transverse tensile strength and proportional limit figures for steels I-1 to I-7 inclusive, and for I-31, and the individual longitudinal and transverse ductility and Izod tests.

The two plain nickel-silicon steels without zirconium or cerium, I-1 and I-2 have respectively 0.46 per cent. and 0.35 per cent. carbon. The

others fall between these limits of carbon. Except for I-1 (1.42 per cent. silicon) the silicon content runs from 1.60 to 1.90 per cent.

The tensile strengths and proportional limits of the zirconium and cerium steels fall between those of the high and low carbon plain nickel-silicon steels. The ductility and Izod figures for the zirconium steels show just as much "scatter" as the plain nickel-silicon steels. The transverse ductility figures for the cerium steels are low. These steels, like all the cerium steels, are dirty. Aside from that, in these steels of about 3 per cent. nickel, 1¾ per cent. silicon, the effect of 0.25 per cent to 0.60 per cent. zirconium or of 0.22 per cent. to 0.54 per cent. cerium is indistinguishable. By picking out individual tests one could allege zirconium to confer greater ductility but the series as a whole does not confirm such an allegation.

In the series with higher silicon (I-8 to I-30 inclusive, also I-32) Table 16 shows the steel to be quite sensitive to high carbon. Steels I-8 with 0.46 per cent. I-12 with 0.47 per cent., I-13 with 0.50 per cent., and I-14 with 0.46 per cent. all show low ductility and low Izod value. There is in most of the steels a decided tendency for the Izod value to be higher at say 550-475 Brinell hardness than at 430-400, and then to rise again as the Brinell hardness falls to 350 or below. This obviously indicates an Izod curve of the general form shown at the right in Fig. 23, Chapter 6, and in Fig. 1 Chapter 1. The reduction of area also may show a similar minimum, also shown in Fig. 1.

Steel I-9, plain nickel-silicon, shows both of these phenomena on the longitudinal tests, as does I-10, which contains only 0.03 per cent. to 0.04 per cent. zirconium. Hence this behavior as shown by I-21, with 0.40 per cent. to 0.50 per cent. zirconium, or by I-29, with 0.20 per cent. aluminum, and I-30 with 0.70 per cent. molybdenum, is a characteristic of this type of alloy steel rather than a specific effect of zirconium, aluminum, molybdenum or chromium. The same characteristic is also seen in some of the chromium-nickel steels, as Figs. 1 and 23 show. See pp. 19, 113.

The combined high tensile strength and high ductility of occasional specimens of this type of nickel-silicon steel to which zirconium has been added, gave rise to the war-time interest in these so-called "zirconium" steels. The authors' experience with these steels leads them to believe that this combination of properties is due to the combination of nickel, silicon, and a suitable amount (not too high) of carbon, rather than to the specific action of any zirconium which may be present. In fact, too much zirconium, as in I-23 and I-24, may injure both strength and ductility. If the carbon and silicon are not too high, this type of steel with about 0.25 per cent. zirconium may give such a combination as 282,000 pounds tensile strength, 220,000 pounds proportional limit, over 7 per cent. elongation and over 30 per cent. reduction of area, at about 500 Brinell hardness.

But I-30, a nickel-silicon-molybdenum steel, gives equally good values, as does the last steel in Table 15, p. 206.

Several of these steels in the very hard condition show a higher or relatively higher proportional limit when drawn at say 400° C. (750° F.)

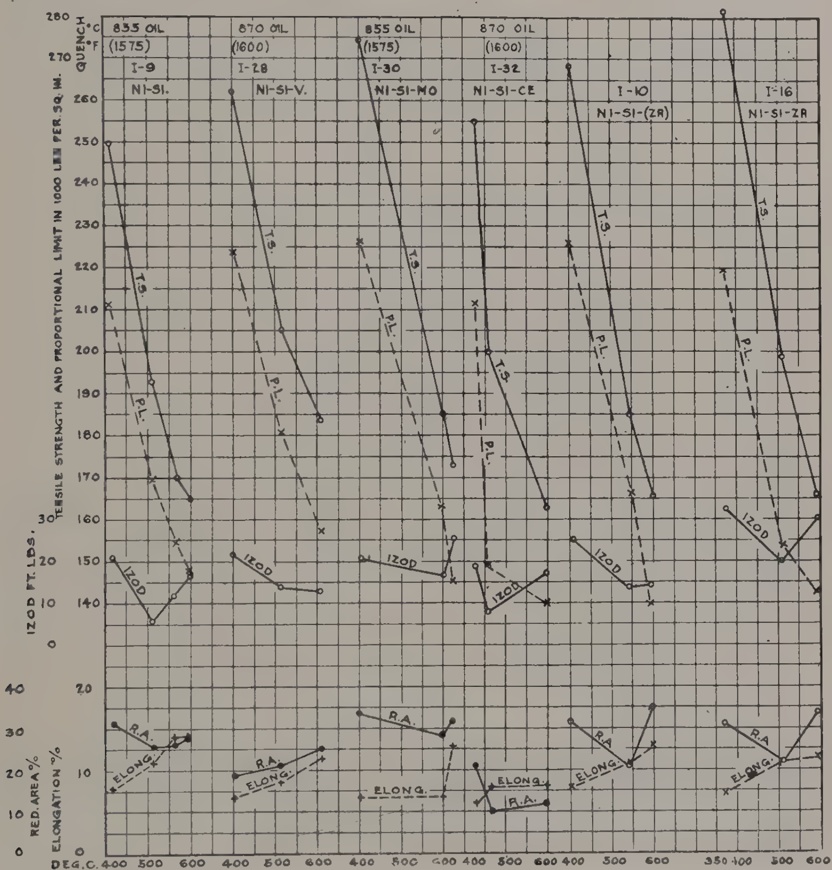


FIG. 57a.—Properties of Ni-Si, Ni-Si-V, Ni-Si-Mo and Ni-Si-Ce steels on longitudinal bars.

than when drawn at lower temperatures, as shown by the following:

	Draw Temp. ° C.	° F.	Brinell	P. L.	T. S.	Elong. Per Cent.	R. A. Per Cent.	Izod
I-4DL	400	750	505	209,000	248,500	8.5	33	24
I-4BL	425	800	460	202,500	222,000	9	35.5	24
I-5BL	345	650	555	224,000	273,000	7	31.5	22.5
I-5AL	400	750	505	224,000	254,500	6	28	18.5
I-6CL	345	650	510	188,500	241,500	6	21	19.5
I-6AL	370	700	505	201,500	242,500	4	13	19
I-7DL	345	650	490	188,000	238,000	6.5	31	20.5
I-7AL	400	750	475	200,000	228,500	7.5	29	14
I-21CT	345	650	505	202,000	253,500	7	28.5	25
I-21AT	400	750	505	209,000	247,000	6.5	23.5	18

Since the elastic ratio is raised by the higher draw in steels I-4 and I-5 without zirconium, it is probable that this phenomenon is due to the release of internal stress by drawing at a higher temperature, rather

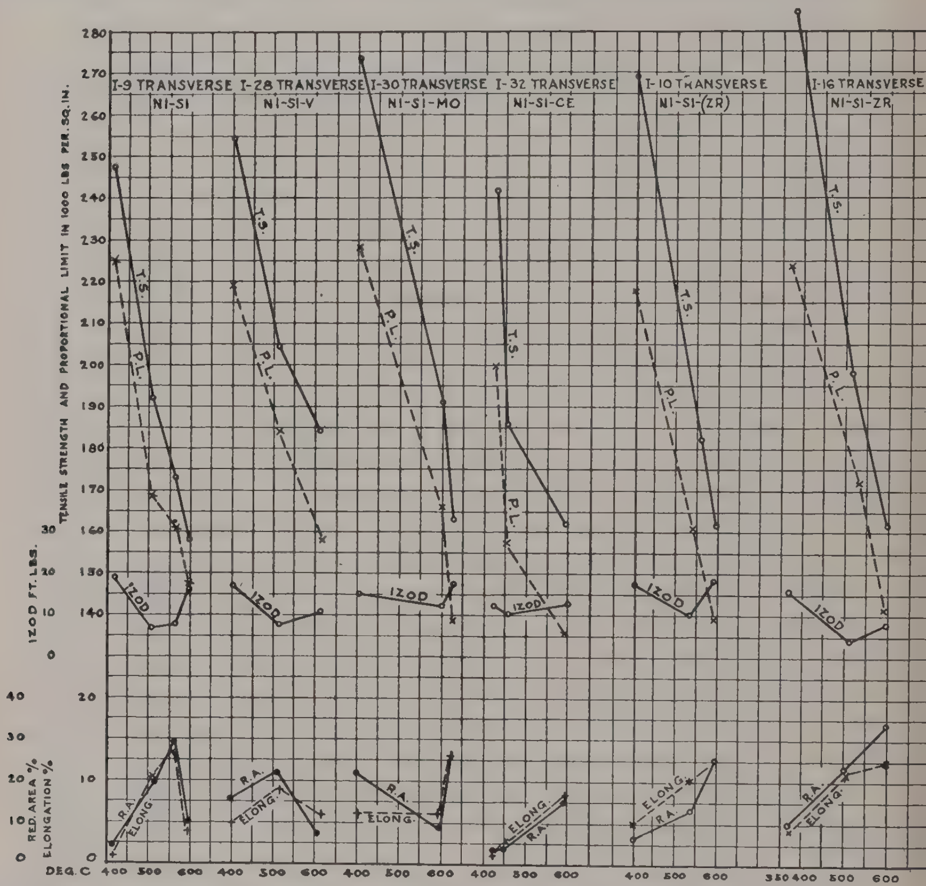


FIG. 57b.—Properties of Ni-Si, Ni-Si-V, Ni-Si-Mo and Ni-Si-Ce steels on transverse bars.

than to a higher zirconium content in the "A" plates of I-6, I-7 and I-21 over that in the "C" or "D" plates. Aitchison (184) discusses the low apparent elastic limit of steel that has been drawn at a temperature too low to release the internal stress.

These nickel-silicon steels remain hard at rather high draw temperatures and if they can be controlled so as to avoid the occasional specimen of low ductility, should make good spring steels. They are probably less prone to low ductility than the comparable "silico-manganese" spring steels, the nickel making them somewhat less erratic.

We may select a few of the many steels of this series of the higher

silicon content for plotting to examine the effect of molybdenum and cerium. We may take the following:

No.	C	Si	Mn	Ni	Zr	V	Mo	Ce	Oil Quenched from °C.	°F.
I-9	.41	2.47	.70	3.00	...	...	...	...	860	1575
I-10	.40	2.73	.57	2.95	.03	...	...	...	860	1575
I-16	.43	2.40	.57	3.00	.22	...	...	...	860	1575
I-28	.36	2.42	.51	2.94	...	.12	...	...	870	1600
I-30	.37	2.50	.52	2.95	...	...	.70	...	860	1575
I-32	.43	2.54	.91	2.86	...	...	...	{ .33 .58	860	1575

These data are shown graphically in Fig. 57. With the exception of generally low ductility (and low strength on the 455° C. (850° F.) draw) for the cerium steel, the results show no one steel to be much different from any other.

The molybdenum steel is a little the strongest at the 400° C. (750° F.) draw, and noticeably so at the 595° C. (1100° F.) draw. Even after the 620° C. (1150° F.) draw it is stronger than the plain nickel-silicon or nickel-silicon-zirconium steel at 595° C. (1100° F.). Its ductility is certainly no worse than the average.

The strength of I-16-B is mostly due to the lower draw temperature rather than to its composition. The action of molybdenum, although not very marked in this type of steel, is yet perfectly consistent in I-30 with its general behavior as an alloying element. The nickel-silicon-vanadium steel I-28 shows up as well, on the whole, as the nickel-silicon-molybdenum steel in strength, but does not average quite as well in ductility, although no very useful comparisons can be made in regard to molybdenum and vanadium because only a single ingot of each was tested.

The addition of cerium in I-31 and I-32 is again detrimental to ductility, just as it was found to be in the other types of steels.

It appears to the authors that the zirconium and titanium of these steels act like so much silicon, to which these elements are chemically related. There are shown in Fig. 58, averaged from the data of Table 16, the properties to be expected from different carbon and silicon contents, or from these elements plus zirconium and titanium if the latter are considered as so much silicon.

It should be emphasized that these comments are not meant to give the idea that zirconium may not be a more effective scavenger, "fixer" of sulfur and controller of phosphorus than silicon, as stated by Becket and Feild.[12, 74-76, 287] The authors have no experimental evidence one way or the other on this point. In the high-silicon steels, the large amount of weak scavenging agent present would make it difficult for a small amount of a stronger scavenging agent to show any effect.

Endurance tests were made on a few nickel-silicon steels selected from the series. The endurance limit of these is given in the last column of

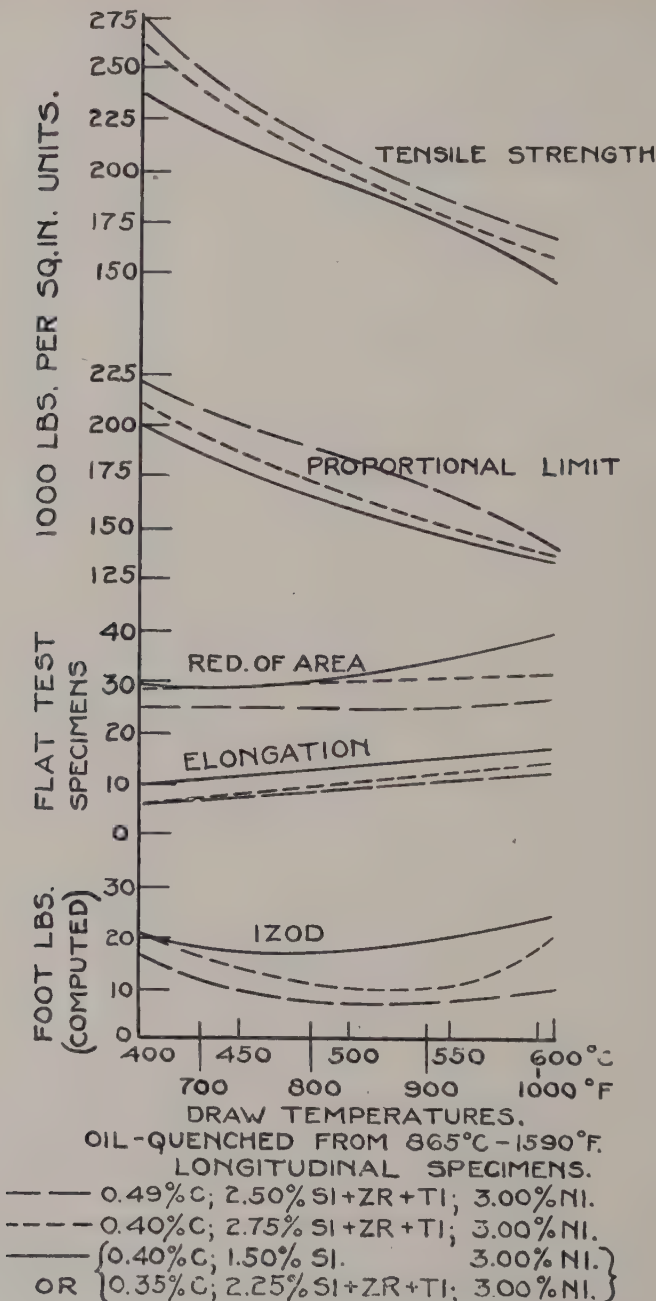


FIG. 58.—Average properties of the Ni-Si type of steel.

Table 16, and is plotted in Fig. 59. The curve of Fig. 32 has been drawn in Fig. 59, and it is seen that these nickel-silicon steels, tested as flat, necked specimens in reversed bending on the Upton-Lewis machine, agree fairly well with that curve, and Fig. 59 indicates even more strongly than Fig. 32 that the tensile strength-endurance limit curve is not a straight line.

The results on transverse specimens average somewhat lower than those on longitudinal specimens, but do not run very much below them, except in the hardest steels. These plates received some cross-rolling, while those described in Chapter 10 did not.

The cerium steel I-32 in this nickel-silicon series gave results at the two lower temperatures very materially below those of similar steels without cerium. As Plate 15-c-d shows, No. I-32 was very dirty. That the endurance results at the highest draw temperatures were so nearly normal, although well below the other nickel-silicon steels of equal tensile strength, indicates that the effect of inclusions is less serious in the softer steels than in the harder ones.

The dirtiness is seen to be bad enough in the bottom or "C" plate with 0.33 per cent. cerium and the worst possible in the top or "A" plate with 0.58 per cent. cerium. The fracture of the endurance specimens varied from fine porcelainic (Plate 15 a) in the "C" specimens to the laminated fracture of the transverse "A" specimens. (Plate 15 c)

Plate 16 shows cross sections cut at right angles to the direction of rolling of a plain nickel-silicon, a nickel-silicon-zirconium and a nickel-silicon-cerium steel. The inclusions in the zirconium and cerium steels are much smaller and much more numerous than in the plain nickel-silicon steel.

On steels I-9 and I-10 it will be noted (see Table 16) that the steels drawn three times with the last draw at 595° C. (1100° F.), show rather better endurance limits than those drawn but once at that temperature.

On I-16-B, which was the strongest steel of the series, due to its carbon content and low draw temperature, most of the transverse specimens broke at the upper jaw of the endurance testing machine instead of at the minimum section. The figure in the table is estimated from the specimens which broke properly.

On the molybdenum steel I-30, no longitudinal specimens were available at the lowest draw temperature, and transverse specimens were tested for that draw. Of the longitudinal specimens for the other three draws, those with a final draw at 595° C. (1100° F.), although preceded by five other, lower temperature, draws gave an endurance limit falling on the usual curve, while those drawn two or three times at 595° C. (1100° F.) to 620° C. (1150° F.) give endurance limits lying above the curve. All three endurance limits have the same numerical value, notwithstanding the

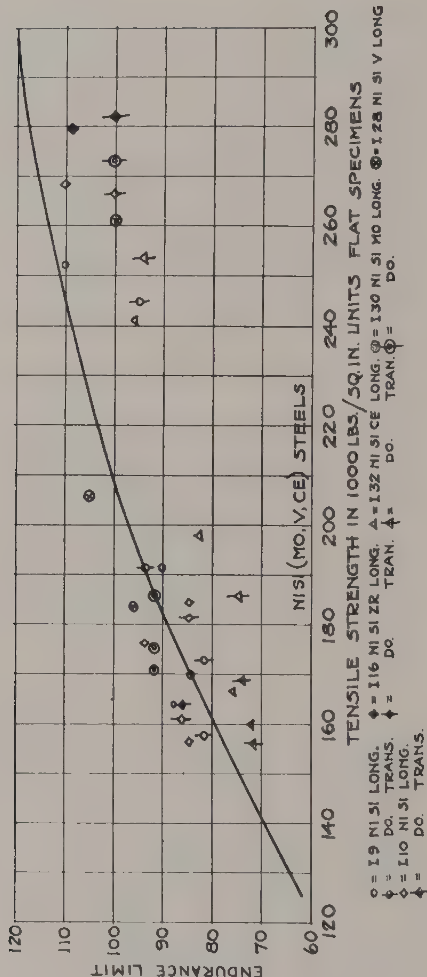
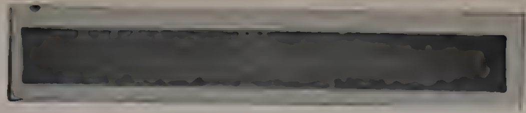


Fig. 59.—Relation of endurance limit to tensile strength in the Ni-Si type of steel. The curve is that of Fig. 32; a curve to represent the average of the points plotted would be almost horizontal beyond 240,000 tensile.



15a × 2½.

Smooth fracture of endurance specimen from plate rolled from bottom of ingot I-32.

15b Un-etched. × 100.

Section from plate rolled from bottom of ingot, nickel-silicon-cerium steel No. I-32. Direction of rolling normal to plane of paper. Cerium content 0.33 per cent.

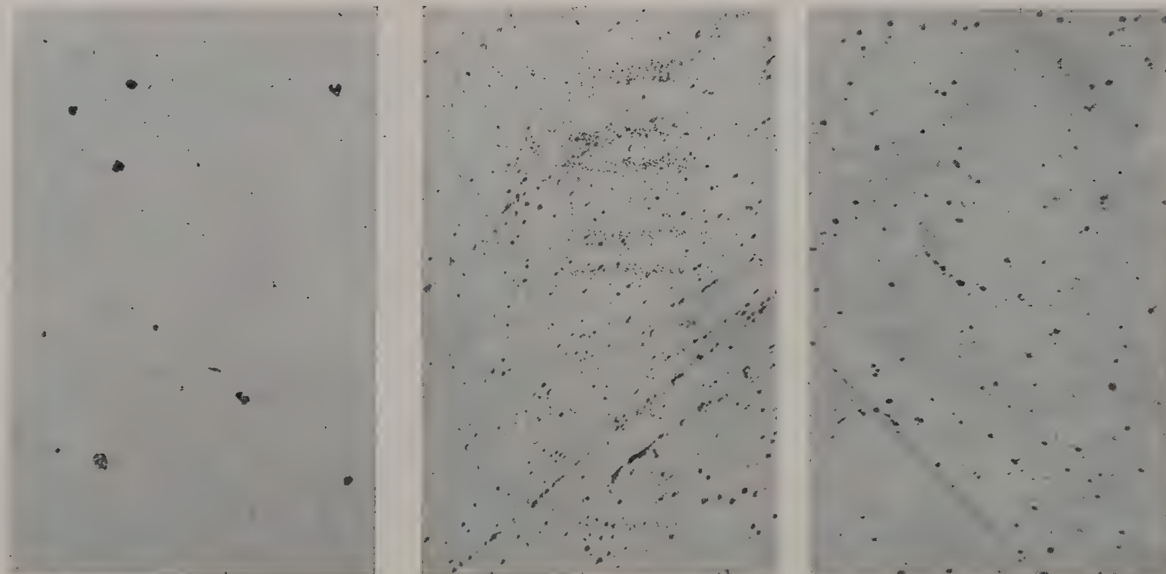
15c × 2½.

Laminated fracture of endurance specimen from plate rolled from top of ingot I-32.

15d Un-etched. × 100.

Section from plate rolled from top of ingot, nickel-silicon-cerium steel No. I-32. Direction of rolling normal to plane of paper. Cerium content 0.58 per cent.

PLATE 15.—Fractures and inclusions, specimens from top and bottom of nickel-silicon-cerium steel No. I-32.



16a
Inclusions in nickel-silicon steel No. I-8.

16b
All un-etched. × 100.
Inclusions in silicon-zirconium steel No. I-24.

16c
Inclusions in nickel-silicon-cerium steel No. I-31.

PLATE 16.—Inclusions in nickel-silicon steel, with and without zirconium or cerium.

differences in tensile strength. That is, at the higher draw temperature the endurance limit does not fall off as fast as does the tensile strength.

The vanadium steel I-28 does not show up as well as the other nickel-silicon steels at the lowest draw temperature, but at the two higher draws gives good results. Both of the higher temperature draws were made after several preliminary draws at lower temperatures.

Leaving out of consideration the dirty cerium steel, and the transverse specimens, we find that out of eleven lots drawn so as to have tensile strengths of 155,000-210,000 pounds, only two give endurance limits below the curve of Fig. 59, and the straight line relation between tensile strength and endurance limit in these steels (drawn for much longer times than is common) represents the points better than the curve of Fig. 32. This indicates clearly that it is the presence of internal quenching stress which causes the plot of Fig. 32 to curve at 175,000 tensile strength for steels drawn for only one hour.

The behavior of this series of steels again indicates that it is the tensile strength, the freedom from internal stress, and the freedom from inclusions which are the determining factors in the endurance properties of heat-treated alloy steels, rather than the chemical composition of the steel.

Chapter 12.

Summary of the Effect of Molybdenum and Cerium as Alloying Elements in Steel.

Cerium appears to have no true alloying effect in steel and to do no good. Since it gives rise to inclusions, it probably does harm. There is a possibility that it might be used as a scavenger to eliminate or control sulfur if means could be found to eliminate the accompanying inclusions.

Molybdenum is a very potent alloying element. Even small amounts greatly increase the propensity of steel toward hardening on quenching. This property is increased in the presence of other hardening elements. That is, molybdenum intensifies the hardening effect of other alloying elements.

After hardening by quenching, the molybdenum steels require decidedly higher draw temperatures to soften them to the same degree as other similar alloy steels. Heat-treated molybdenum steels of a given strength or hardness can therefore be produced by the choice of a suitable composition of the steel as to molybdenum and other alloying elements, in which, by a long draw at a high temperature, quenching stresses can be largely relieved without softening the steel beyond the desired point. The ductility of the molybdenum steels at a given hardness, tensile strength, or elastic limit, is equal to that of any other and superior to most alloy steels. The great resistance to tempering makes the molybdenum steels attractive for use where strength at high temperatures is desired.

When a very high tensile strength at ordinary temperatures is sought, molybdenum again offers a ready and certain means of attaining the result desired. For strengths which can be readily obtained by other heat-treated alloy steels, the use of molybdenum appears to allow as great a latitude in forging and quenching temperatures as is safe with any other alloy steels, and greater than is safe with some others.

If a steel is to be used in the normalized condition, its molybdenum content should preferably be low. Steels in which the addition of molybdenum has produced a strong tendency toward air-hardening do not give very good results in the normalized state, unless a low proportional limit can be tolerated. In general, the molybdenum steels should be heat-treated to develop the best combination of properties.

When heat-treated molybdenum steels are compared with other alloy

steels on the basis of tensile strength or Brinell hardness, their behavior on repeated-impact or single notched-bar tests is the same as that of the others.

The endurance properties of molybdenum steels, again compared with other alloy steels on the basis of strength or hardness, are substantially the same as those of other alloy steels.

If the comparison is made on the basis of the same heat-treatment, especially at the same draw temperature, the molybdenum steels are stronger in endurance test and weaker in shock test, but this is because the molybdenum steels resist tempering more than the other steels and are therefore harder, stronger in tension, and less ductile. At a very high strength and hardness, the endurance properties of a molybdenum steel subjected to a long tempering process at a high temperature will probably be superior to those of other steels (which, in order to get this high strength, may only be tempered at much lower temperatures), because of the better release of quenching stresses. Within the machineable range this advantage is probably slight.

Tests of transverse specimens of molybdenum steels show lower ductility, endurance and shock resistance than do longitudinal tests, and the specimens may show a woody fracture. But this behavior is in no way due to the presence of molybdenum. Similar steels without molybdenum and similar steels with vanadium in place of molybdenum show the same behavior to an equal degree. The differences between longitudinal and transverse tests seem primarily due to non-metallic inclusions.

Molybdenum is not a deoxidizer or scavenger of steel. Molybdenum steels are neither more nor less prone to dirtiness than similar steels without molybdenum. A molybdenum steel improperly made can be as dirty and as poor as any other similar improperly-made steel.

The advantage of better machineability claimed for molybdenum steel has not been quantitatively tested in this work, but many of the harder steels containing molybdenum were sawed and machined without as much difficulty as would have been expected.

These various properties conferred on steel by molybdenum are observed whether the steel to which molybdenum is added is a plain carbon steel, a carbon steel high in manganese, a chromium, a nickel-chromium, or a nickel-silicon steel. The effect of a small amount of molybdenum is more marked in a less highly alloyed steel, such as the ordinary chromium steel, than it is in a more highly alloyed steel, such as the "high" nickel-chromium steels. A small amount of molybdenum tends to push a steel over toward the air-hardening side to a degree which would require much larger amounts of the other usual alloying elements.

Broadly speaking, the effect of about 0.40 per cent. molybdenum in a given steel, and that of about 0.20 per cent. vanadium, appears to be

very nearly equivalent when both steels are heat-treated and drawn to the same hardness. The molybdenum steel will usually be slightly more ductile while the vanadium steel will usually have a slightly higher elastic ratio.

The depth-hardening properties of the molybdenum steel are quite definitely greater; in shock tests and endurance tests the two steels behave similarly.

In high speed steels, or in steels for use in the normalized condition, molybdenum is not an equivalent substitute for vanadium. In heat-treated steels considered from the view-point of the engineer, it appears to be such a substitute.

While it is generally considered that increase in vanadium content above 0.20 per cent. brings no advantage in engineering steels, increase in molybdenum content above 0.40 per cent. continues to develop strength.

Properties similar to those obtained through the use of molybdenum can be obtained by various combinations of the other alloying elements, with suitable heat-treatment. However, the control of temperature in quenching and drawing, in order to obtain the desired results must, in general, be closer in the absence than in the presence of molybdenum. Uniformity of product will therefore generally be easier to maintain with the commercial molybdenum steels than with other alloy steels of the usual commercial composition.

When the molybdenum content is very high, or when much molybdenum is added to a steel of the high nickel-chromium class, the control in drawing to a relatively low Brinell hardness would be less easy than without the molybdenum, while in drawing to a spring temper it would be easier. This is because the molybdenum increases the resistance to drawing so that the steel remains hard at high drawing temperatures, but when such a steel finally reaches the temperature at which softening begins, further increase in temperature hastens the softening at a high rate.

While the production of molybdenum steels is not yet large so that some prospective users fear lack of supply or too few sources, this should be remedied as the advantages of molybdenum become better known. The prices of molybdenum alloy steels are no higher and in some cases are lower than those of other alloy steels which can be made to give similar results.

This domestic alloying element should, and doubtless will, find increasing use.

Appendix A.

Composition, Rolling, and Heat-Treatment of the Experimental Molybdenum and Cerium Steels.

The preparation of the steels in the electric furnace, the recovery of alloying elements, the behavior of cerium in desulfurizing steel, and the segregation of cerium have been fully discussed elsewhere.[63, 64]

Composition of Steels Tested

The chemical analysis of the steels tested is given in Table 17. The last column gives the percentage of aluminum added as final deoxidizer and degasifier in the steels made by the authors. It was tossed into the bottom of the ladle before the steel was poured, except in the case of steel No. 32, in which the aluminum was added to the top of the ladle after pouring. The finished steels were not analyzed for aluminum content.

Steels Nos. 1 to 26 inclusive and Nos. 52 to 54 inclusive were rolled from 3 inch x 3 inch ingots to ¾ inch round bar. Steels Nos. 39 to 44 inclusive were forged to 1½ inch round bar under a steam-hammer at a local (Ithaca, N. Y.) shop, and later rolled to ¾ inch round bar. Steels Nos. 27 to 37 inclusive were rolled from 3 inch x 6 inch ingots to 6 inch x 0.6 inch plates. Steels Nos. 53 and 54 were forged from 3 inch x 3 inch ingots to ⅞ inch round bar under a steam-hammer in the local shop. All these steels were made by the authors in the electric furnace laboratory of Cornell University. The letter "A" after the heat number refers to the first ingot poured, the letter "B" to the second ingot. The other steels were obtained from the following sources:

No.	Maker	Process	Size in Which Received
45	United Alloy Steel Co.	Electric	1″ round
46	United Alloy Steel Co.	Open hearth	1″ round
47	Crucible Steel Co.	Electric	1″ round
48	Crucible Steel Co.	Electric	1″ round
49	Crucible Steel Co.	Electric	1″ round
50	Electric Alloy Steel Co.	Electric	1″ round
51	Electric Alloy Steel Co.	Electric	1″ x ¼″
55	United Alloy Steel Co.	Electric	¾″ round
57	United Alloy Steel Co.	Open hearth	¾″ round

The maker's analyses are given for these steels. No data are available as to the amount of aluminum, if any, used as deoxidizer.

TABLE 17

No.	Heat	C	Si	Mn	S	P	Ni	Cr	Mo	V	Ce	Al Added
1	1335A	.40	.29	.77	.035	.010	...	...	...	...	...	.02
2	1336A	.41	.42	.72	.020	.010	...	...	.67	...	...	.01
3	1337A	.38	.35	.71	.023	.010	...	...	.37	...	...	.01
5	1339A	.38	.35	.68	.016T .007B	.006	...	...	...	...	.61T .41B	...
6	1340A	.44	.30	1.05	.040	.010	...	...	...	...	...	.01
7	1341A	.43	.46	1.24	.019	.010	...	...	.73	...	...	.01
8	1342A	.44	.33	1.29	.019	.010	...	...	.34	...	...	.01
9	1343A	.35	.35	.62	.031	.010	...	.94	...	...	...	.01
10	1344A	.40	.40	.62	.030	.010	...	.95	.68	...	...	.01
11	1345A	.41	.28	.63	.028	.010	...	.89	.36	...	...	.01
12	1346A	.40	.31	.64	.032	.010	...	.93	...	.20	...	...
13	1347A	.41	.27	.64	.019T .007B	.012	...	.98	...	...	.34T .32B	.005
14	1347B	.41	.27	.64	.021T .007B	.010	...	.99	...	...	.50T .41B	.005
15	1348B	.47	.30	.64	.029	.014	1.23	.65	...	...	...	.01
16	1349A	.41	.41	.64	.017	.009	1.27	.67	.83	...	...	.01
17	1350A	.39	.27	.66	.023	.009	1.28	.68	.31	...	...	.01
18	1351B	.39	.28	.71	.035	.010	1.20	.74	...	.24	...	...
20	1365A	.41	.33	.63	.031T .006B	.007	1.17	.77	...	...	.25T .25B	.005
21	1353A	.36	.33	.65	.038	.013	2.56	.83	...	...	...	less than .01
22	1369A	.41	.31	.60	.021	.018	2.49	.79	.76	...	...	.01
23	1355A	.46	.32	.61	.025	.017	2.45	.88	.35	...	...	.01
24	1356A	.40	.28	.61	.029	.010	2.52	.84	...	.20	...	....
25	1357A	.43	.35	.58	.017T .017B	.008	2.47	.95	...	...	.22T .25B	.005
26	1358A	.50	.44	.63	.029	.012	2.39	.86	.75	...	...	.01
27	1359	.45	.27	.62	.015	.009	...	.92	...	...	...	.01
28	1360	.42	.35	.67	.021	.012	...	.93	.73	...	...	.01
29	1361	.38	.30	.65	.023	.014	...	.84	.35	...	...	....
30	1362	.37	.32	.69	.034	.009	...	.97	...	.24	...	....
32	1364	.37	.28	.63	.036	.011	2.49	.83	...	...	...	.01*
33	1366	.38	.48	.61	.018	.015	2.53	.78	.75	...	...	.01

* Aluminum added in top of ladle..

TABLE 17—(*Continued*)

No.	Heat	C	Si	Mn	S	P	Ni	Cr	Mo	V	Ce	A1 Added
34	1371	.44	.43	.66	.018	.017	2.44	.82	.37	...	...	less than .01
35	1368	.41	.34	.58	.037	.013	2.52	.85	...	.19	...	.005
36	1370	.36	.34	.66	.012T .012B	.012	2.46	.92	...	...	.18T .19B	....
37	1367	.53	.36	.65	.018	.012	2.52	.83	.34	...	...	....
39	1088	.50	.59	.42	.032	.011	...	...	1.15	...	...	.02
40	1089	.65	.36	.79	.020	.023	...	...	1.90	...	...	.02
41	1091	.46	.43	.75	.020	.015	...	...	1.05	...	...	.02
42	1092	.36	.40	.67	.020	.024	...	...	2.05	...	...	0.15
43	1096	.39	.24	.66	.035	.025	...	...	1.90	...	...	.02
44	1097	.36	.30	.65	.038	.027	...	...	3.00	...	...	.02
45	32595	.40	.12	.65	.026	.021	...	.88	.30	...	...	....
46	11347	.22	.14	.59	.040	.018	...	.79	.34	...	...	....
47	E116	.15	.12	.36	.006	.014	...	.73	.28	...	...	....
48	E263	.42	.19	.55	.009	.016	...	.55	.39	...	...	....
49	E53	.25	.19	.48	.009	019	...	.95	.73	...	...	....
50	5516	.52	.16	.71	.015	.016	...	.95	.39	...	...	....
51	2462	.53	.17	.84	.012	.018	...	1.09	.44	...	...	....
52	1374A	.54	.48	.84	.013T .011B	.006	1.02	.84	...	...	.42T .36B	....
53	1375	.31	.55	.05T .07M .08B	.020T .009M .009B	.003	...	...	...	...	.15T .13B	....
54	1376	.30	.65	.06T .07M .06B	.032	.005	...	...	...	...	.04T .05B	....
55	32026	.50	.16	.84	.019	.012	...	...	...	.20	...	....
57	19531	.41	.13	.67	.037	.017	...	.93	...	.16	...	....

Both top and bottom samples of the cerium steels were analyzed for cerium and for sulfur. Nos. 4, 19, and 31, not given in the table, were assigned to cerium steels which showed so many hair-cracks that they were discarded. Steel No. 51 was not tested, save for taking critical points and for some preliminary endurance tests made on un-necked specimens, since No. 50 is almost a duplicate. No. 56 was assigned to a steel reputed to be a nickel-vanadium, but which was found to be a high-carbon nickel-chromium-vanadium steel and was not tested. The number 38 was not used. Since Nos. 13 and 14 were from the same heat this leaves 50 distinct steels which were tested in the molybdenum and cerium series.

Of the cerium steels Nos. 5 and 20 showed a few very small hair-cracks both on top and bottom of the ingot. Nos. 13 and 14 showed some on the tops but none on the bottoms. No. 25 showed no cracks on top or bottom on examination of polished faces, but one was developed on the top after deep etching. Nos. 36, 52, 53 and 54 showed no cracks.

Rolling 3 inch x 3 inch ingots and re-rolling of 1½ inch x 1 inch rod

No unusual features were noted in connection with the rolling of the ¾ inch and ⅜ inch round bars. Steels Nos. 5 and 20 containing cerium, which had shown fine cracks in the ingot did not split in rolling. Several inches were sheared from the bottom end of the rough bar before cutting into weights for rounds. This was done to insure a good end with which to enter the various passes of the rolls.

The three inch square ingots were roughed to 1⅛ inch square in 9 passes in the diamond rolls, taken to shears and 6 to 7 pounds cut from the bottom end for ⅜ inch rounds. The average temperature before rolling was 1130° C. (2065° F.).

The 1⅛ inch square rough bar was rolled to ¾ inch round in 9 passes in diamond rolls, 8 passes in breaking down round rolls, and 6 passes in the finishing rolls, a total of 23 passes, which together with 9 roughing passes makes a total of 32 passes from 3 inch square ingot to finished bar. The average temperature before rolling was 1180° C. (2155° F.) and after rolling was 750° C. (1380° F.).

The ⅜ inch rounds were rolled by guide from 1⅛ inch square rough bar in 5 passes in diamond rolls, 3 passes in oval and 3 passes in square alternately and one oval pass before the final finishing pass, a total of 13 passes or 22 passes from ingot to finished bar. The ⅜ inch rounds of Nos. 39 to 44 inclusive, were rolled from previously forged 1½ inch round bars from ingots made in a previous investigation. Some ⅜ inch rod was rolled from the 1 inch rod of steels No. 45 to 50 inclusive, obtained from outside makers. The average temperature before rolling was 985° C. (1800° F.) and after rolling was 810° C. (1490° F.).

TABLE 18

Serial No.	Roughing Temp.		No. of Bars	¾ Inch Rounds (Hand) 12 Inch Mill — Furnace Temperature — Bottom Bar		Top Bar		Finishing Temperature — Bottom Bar		Top Bar		⅜ Inch Rounds (Guide) 8 Inch Mill — Furnace Temperature		Finishing Temperature	
	° C.	° F.		° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
1	1125	2055	2	1175	2145	1180	2155	....	....	....	....	980	1795	730	1345
2	1135	2075	2	1195	2185	1195	2185	....	....	....	....	985	1805	745	1370
3	1130	2065	2	1180	2155	1175	2155	....	....	....	....	980	1795	785	1445
5	1125	2055	1	1185	2165	....	....	....	....	....	....	985	1805	810	1490
6	1130	2065	2	1195	2185	1125	2055	....	....	....	....	990	1815	805	1480
7	1125	2055	2	1190	2175	1190	2175	....	....	....	....	995	1825	830	1525
8	1125	2055	2	1185	2165	1185	2165	....	....	....	....	990	1815	810	1490
9	1130	2065	2	1190	2175	1185	2165	755	1390	745	1375	985	1805	830	1525
10	1130	2065	2	1195	2185	1185	2165	755	1390	730	1345	980	1795	820	1510
11	1125	2055	2	1195	2185	1200	2190	755	1390	775	1425	985	1805	830	1525
12	1135	2075	2	1195	2185	1195	2185	720	1330	805	1480	985	1805	840	1545
13	1130	2065	1	1195	2185	....	....	805	1480	....	....	990	1815	850	1560
14	1125	2055	1	1195	2185	....	....	720	1330	....	....	985	1805	855	1570
15	1140	2085	1	1195	2185	....	....	720	1330	....	....	985	1805	810	1490
16	1130	2065	1	1195	2185	....	....	715	1320	....	....	980	1795	840	1545
17	1135	2075	2	1190	2175	1195	2185	755	1390	755	1390	990	1815	850	1560
18	1140	2085	2	1195	2185	1190	2175	720	1330	810	1490	985	1805	820	1510
20	1140	2085	2	1185	2165	1175	2145	755	1390	805	1480	980	1795	810	1490
21	1135	2075	2	1180	2155	1175	2145	710	1310	805	1480	980	1795	840	1545
22	1145	2095	2	1180	2155	1185	2165	720	1330	760	1400	980	1795	810	1490
23	1135	2075	2	1185	2165	1180	2155	755	1390	755	1390	990	1815	795	1465
24	1150	2100	2	1185	2165	1190	2175	670	1240	805	1480	985	1805	820	1510
25	1145	2095	1	1185	2165	....	....	735	1355	....	....	980	1795	810	1490
26	1140	2085	2	1180	2155	1175	2145	775	1425	780	1435	995	1825	830	1525
52	1115	2040	1	1180	2155	....	....	695	1285	....	....	980	1795	850	1560
39	....	....	...	1000	1830	....	....	Below limit of optical pyrometer or about 660° C. (1220° F.)				980	1795	785	1445
40	....	....	...	1005	1840	....	....					980	1795	820	1510
41	....	....	...	1025	1880	....	....					985	1805	820	1510
42	....	....	...	1005	1840	....	....					980	1795	795	1465

TABLE 18—(*Continued*)

Serial No.	Roughing Temp.		No. of Bars	¾ Inch Rounds (Hand) 12 Inch Mill: Furnace Temperature, Bottom Bar		Furnace Temperature, Top Bar		Finishing Temperature, Bottom Bar		Finishing Temperature, Top Bar		⅜ Inch Rounds (Guide) 8 Inch Mill: Furnace Temperature		Finishing Temperature	
	° C.	° F.		° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
43	....	....	...	975	1785	....	....	Below limit of optical pyrometer or about 660° C. (1220° F.)				985	1805	810	1490
44	....	....	...	1020	1870	....	....					970	1780	775	1425
45	....	....	...	....	....	....	....					985	1805	830	1525
46	....	....	...	....	....	....	....					990	1815	820	1510
47	....	....	...	....	....	....	....	....	....	....	....	995	1825	795	1465
48	....	....	...	....	....	....	....	....	....	....	....	980	1795	830	1525
49	....	....	...	....	....	....	....	....	....	....	....	995	1825	810	1490
50	....	....	...	....	....	....	....	....	....	....	....	990	1815	830	1525

On steels No. 1 to 26 inclusive and on steel No. 52, the ⅜ inch rod for endurance specimens was rolled from the bottom end of the ingot. On steels Nos. 39 to 44 and Nos. 45 to 50 inclusive the forged bars had not been marked to show which was the bottom end. The position of the bar in reference to the original ingot consequently was not known.

Table 18 gives temperature data before and after rolling.

All of the ¾ inch rounds were annealed at about 815° C. (1500° F.) and slowly cooled. The ⅜ inch rounds were not annealed.

Among the 0.6 inch x 6 inch flats six pieces showed a Brinell number over 250 and consequently these pieces were sent back for further softening treatment.

The three heats which were re-annealed were all nickel-chromium-molybdenum steels and were probably stripped from the furnace when at 500° C. (930° F.) or above.

Rolling of 0.6 inch x 6.0 inch flats

The 6 inch x 3 inch ingots were broken down in the box passes to about 1½ inch in 5 to 6 passes, then edged and broken down to slightly oversize in 5 edging passes and 4 flat passes and then finished in 2 passes in the strand rolls. The total time of raising the heat and soaking was 2 hours. The serial numbers and starting and finishing temperatures are tabulated below:

	Temperature at Start of Rolling		Temperature at End of Rolling	
Serial Number	° C.	° F.	° C.	° F.
27	1100	2010	910	1670
28	1080	1975	905	1660
29	1075	1965	910	1670
30	1085	1985	945	1735
32	1065	1950	930	1705
33	1065	1950	940	1725
34	1045	1915	965	1770
35	1045	1915	935	1715
36	1040	1905	940	1725
37	1035	1895	780	1435

The last ingot, No. 37, curled into a semi-circle after the first pass in the strand roll. It resisted all efforts to straighten it by means of the roller's tongs so that the finishing temperature is much lower.

The rolled plates were annealed at 800° CC. (1470° F.) in pots for 10 hours. All the ingots were surface-ground until free from all visible imperfections. The rolling was done at cost by the Halcomb Steel Company at Syracuse, N. Y., and was carried out with great care by the management and workmen. The quality of the work was very high.

Heat-Treatment

The test specimens were mostly heat-treated in gas-fired furnaces whose temperature as well as that of the drawing furnaces was recorded on a Leeds and Northrup potentiometer by base metal thermocouples. Couples were frequently checked against a standard platinum couple. Some specimens were treated in a Leeds and Northrup electric furnace, regulated by a contact-making and recording potentiometer. The pieces were charged into the cold furnace and brought up to temperature with it. They were held at the quench temperature 25 to 35 minutes. If held for a longer or shorter time the fact is noted in Table 19.

Quenching was done in 20 gallon volumes of water, Houghton's soluble quenching oil No. 2, or Franklin quenching oil. Care was taken that the temperature of the quenching medium should not increase materially.

Immediately after quenching the specimens were transferred to the draw furnaces (which were already warm) without being allowed to become entirely cold. The temperature was raised slowly to the desired draw temperature and maintained one hour when the pieces were withdrawn and cooled in air. Drawing was done in air or, for temperatures of about 425° C. (800° F.) in a bath of fused sodium and potassium nitrates, always used for this temperature unless otherwise noted. For some special low temperature draws an electrically heated oil bath was used. In every case the steel was held at the draw temperature one hour. In some of the earlier heat-treatments each specimen was quenched individually, but most of them were handled in frames which, while keeping each specimen well separated from the adjacent ones, allowed discharging the furnace more rapidly and with less change in temperature from opening the door. When quenching frames were not used, the fact is noted. The specimens were kept in motion during quenching. No specimens were quenched after the draw except in a few re-drawing tests discussed in the text. Some of the test-specimens (those from one group of plates) were cooled in the furnace, but the usual cooling was in air.

Some of the tensile, Stanton, and Izod specimens were first normalized, but as a rule the steels in the small specimens used responded readily to a single quench and draw without either normalizing or double treatment. Nos. 53, 54, and 55 are the only steels on which the endurance specimens were normalized before quenching. The steels were rough machined to test-piece form, leaving about 1/16 inch finish for grinding They were then heat-treated, and ground to size. It was thought best to heat-treat these pieces in as small a size as possible to make them more nearly comparable with the small endurance test-pieces. In the few cases noted in the table, where the specimens were normalized before heat-treatment they were normalized before machining, *i.e.,* in the original

diameter of the rod. Most of the Upton-Lewis endurance specimens were taken from ⅜ inch rod cut into 6 inch lengths. On some of the steels received from outside makers later in the investigation the Upton-Lewis test-pieces were turned, before heat-treatment, from 1 inch or ¾ inch rounds down to ⅜ inch.

All the Upton-Lewis specimens were heat-treated in 6 inch x ⅜ inch. On account of the small size of the pieces used, no information was gained on the question of depth hardening, and the specimens are doubtless generally harder and stronger than would be the case in the heat-treatment of larger masses of the same steels.

Since it is well known that molybdenum steels are equal to any and superior to many in depth hardening, the tests herein recorded do not tend to show as great a difference between molybdenum and other steels under the same heat-treatment as would have been the case with tests on the steels heat-treated in greater mass, making the comparison not so favorable to molybdenum steels as it could have been made.

The ¾ inch rod from which tensile, Stanton, and Izod test-pieces were made was annealed at 815° C. (1500° F.) and furnace cooled, except on steels Nos. 53, 54, 55, and 57. The ⅜ inch rod from which Upton-Lewis test-pieces were made was not annealed. The plates (27 to 30 inclusive and 32 to 37 inclusive) were annealed at 800° C. (1470° F.) and furnace cooled.

Because the literature contains very little data on endurance of steels of "spring temper" the steels were given one relatively low-temperature draw so that on most of the steels draw No. 1 gives a Brinell hardness of 360-420.

The data on heat-treatment are recorded in Table 19.

TABLE 19

	Quench			Draw Temperature						
				Draw #1		Draw #2		Draw #3		
No.	° C.	° F.	Medium	° C.	° F.	° C.	° F.	° C.	° F.	Remarks
1	870	1600	Water	300	570	360	680	420	790	Draw 4 at 425° C. (800° F.) as a separate lot of endurance specimens only, at heat 15 minutes. No frame used except on specimens for 425° C. (800° F.) draw.
2	870	1600	Water	360	680	420	790	500	930	No frames. Special normalizing tests (1) 900° C. (1650° F.) 20 minutes at heat, air-cooled, (2) 840° C. (1545° F.) 55 minutes at heat, air-cooled.
3	870	1600	Water	300	570	370	700	430	805	No frames. Special normalizing tests (1) 900° C. (1650° F.) 20 minutes at heat, air-cooled, (2) 840° C. (1545° F.) 55 minutes at heat, air-cooled.
4	...	....	......	...	...	...	...	...	...	Cracked ingot, not tested.
5	870	1600	Water	300	570	370	700	430	805	No frames.
6	875	1610	Oil	350	660	400	750	450	840	No frames, at heat 20 minutes, 350° C. (660° F.) draw in salt bath.
7	875	1610	Oil	400	750	475	885	550	1020	At heat 20 minutes, no frames.
8	875	1610	Oil	375	710	450	840	525	975	No frames.
9	925	1700	Oil	425	800	525	975	625	1150	No frames.
10	900	1650	Oil	425	800	525	975	625	1150	At heat 20 minutes.
11	900	1650	Oil	425	800	525	975	625	1150	Normalized specimens, normalized in ¾ inch size.
12	900	1650	Oil	425	800	525	975	625	1150	Special tests, annealed 825° C. (1515° F.) at heat 30 minutes, furnace cooled, normalized 900° C. (1650° F.) at heat 30 minutes, air-cooled.
13	900	1650	Oil	425	800	525	975	625	1150	At heat 20 minutes.
14	900	1650	Oil	425	800	525	975	625	1150	At heat 20 minutes.
15	825	1515	Oil	425	800	525	975	625	1150	Time "at heat" under remarks means before quenching. All draws held at heat 1 hour.
16	825	1515	Oil	425	800	525	975	625	1150	
17	825	1515	Oil	425	800	525	975	625	1150	
18	825	1515	Oil	425	800	525	975	625	1150	
19	...	....	......	...	...	...	...	...	....	Cracked ingot—not tested.
20	825	1515	Oil	420	790	525	975	625	1150	
21	810	1490	Oil	425	800	525	975	625	1150	

TABLE 19—(*Continued*)

	Quench			Draw Temperature						
				Draw #1		Draw #2		Draw #3		
No.	° C.	° F.	Medium	° C.	° F.	° C.	° F.	° C.	° F.	Remarks
22	805	1480	Oil	425	800	525	975	625	1150	Also 10 other extra draws referred to in text.
23	810	1490	Oil	425	800	525	975	625	1150	At heat 20 minutes.
24	815	1500	Oil	425	800	525	975	625	1150	
25	810	1490	Oil	430	805	525	975	625	1150	
26	790	1455	Oil	430	805	525	975	625	1150	
27	900	1650	Oil	550	1020	650	1200	...	....	Plate; 650° C. (1200° F.) draw, furnace cooled from draw.
28	900	1650	Oil	550	1020	...	....	...	....	Plate.
29	900	1650	Oil	550	1020	...	....	...	....	Plate.
30	900	1650	Oil	550	1020	...	....	...	....	Plate; at heat 40 minutes.
31	...	....	......	...	....	...	...	...	....	Cracked ingot—not tested.
32	805	1480	Oil	485	900	...	...	...	....	Plate; furnace cooled from draw.
33	805	1480	Oil	635	1175	...	...	...	....	Plate; furnace cooled from draw.
34	805	1480	Oil	635	1175	...	...	...	....	Plate; furnace cooled, previously drawn at 610° C. (1130° F.). Not soft enough.
35	805	1480	Oil	540	1000	...	...	...	....	Plate; double treated; 1st, 805° C. (1480° F.), 560° C. (1040° F.) draw, too soft; furnace cooled from draw, re-treated.
36	805	1480	Oil	500	930	...	...	...	....	Plate; double treated; 1st, 805° C. (1480° F.), 560° C. (1040° F.) draw, too soft; furnace cooled from draw, re-treated.
37	790	1455	Oil	620	1150	...	...	...	....	Plate; double treated; 1st, 805° C. (1480° F.), 560° C. (1080° F.) draw, too soft; furnace cooled from draw, re-treated.
38	...	....	......	...	....	...	...	...	....	
39	850	1560	Oil	425	800	525	975	625	1150	Specimens, except endurance specimens, cooled in furnace, with door open, from 900° C. (1650° F.) before heat-treatment, ¾ inch round.
40	825	1575	Oil	...	...	550	1020	625	1150	Specimens, except endurance specimens, from ¾ inch round, 870° C. (1600° F.), cooled in furnace with door open, before heat treatment.
41	900	1650	Oil	425	800	525	975	600	1110	Specimens, except endurance specimens, from ¾ inch round, normalized 900° C. (1650° F.) in air before heat-treatment, no frames.

TABLE 19—(*Continued*)

No.	Quench °C.	Quench °F.	Quench Medium	Draw #1 °C.	Draw #1 °F.	Draw #2 °C.	Draw #2 °F.	Draw #3 °C.	Draw #3 °F.	Remarks
42	875	1600	Oil	...	...	550	1020	650–660	1200–1220	Specimens, except endurance specimens, first normalized in ¾ inch round, 900° C. (1650° F.) air.
	925	1700	Water	...	...	545	1010	...	....	Water-quenched specimens were previously oil-quenched and drawn at 650° C.–660° C. (1200°–1220° F.), temperature fluctuated during draw, re-quenched and tempered at 545° C. (1010° F.)
	900	1650	Oil	...	...	500	930	600	1110	Endurance specimen only 900° C. (1650° F.) oil, not normalized, no frames.
43	775	1425	Oil	...	...	550	1020	650–660	1200–1220	Specimens, except endurance specimens, first normalized in ¾ inch round.
	925	1700	Water	...	...	...	....	650	1200	Water-quenched specimens previously oil-quenched at 775° C. (1425° F.) drawn at 650° C.–660° C. (1200°–1220° F.), re-quenched, and tempered at 650° C. (1200° F.).
	900	1650	Oil	425	800	600	1110	650	1200	Endurance specimens only at 900° C. (1650° F.), oil, not normalized; no frames. 650° C. (1200° F.) draw specimens were first drawn at 500° C. (930° F.) gave 418 Brinell hardness, redrawn at 650° C. (1260° F.).
44	900	1650	Oil	425	800	500	930	575	1245	Specimens, except endurance specimens, heated to 900° C. (1650° F.) in ¾ inch round and cooled in furnace with door open before heat-treatment. Frames used on endurance specimens only.
45	820	1510	Oil	425	800	525	975	625	1150	All specimens, except endurance specimens, normalized in 1 inch round from 900° C. (1650° F.) air, before heat-treatment.
	900	1650	Oil	...	...	525	975	...	1150	Tensile specimens heat-treated in 1 inch round; all others in 1/16 inch over-size. Endurance specimens at heat 15 minutes, and others 45 minutes. Endurance bars 1/16 inch over-size. Special heat; endurance bars only.
46	850	1560	Water	...	...	525	975	625	1150	All specimens, except endurance specimens, normalized in 1 inch round from 900° C. (1650° F.) air, before heat-treatment in 1 inch round, all others in 1/16 inch round over-size. Endurance specimens at heat 15 minutes, all others 45 minutes. Endurance specimens 1/16 inch over-size.

TABLE 19—(*Continued*)

No.	Quench °C.	Quench °F.	Quench Medium	Draw #1 °C.	Draw #1 °F.	Draw #2 °C.	Draw #2 °F.	Draw #3 °C.	Draw #3 °F.	Remarks
46	850	1560	Oil	...	...	525	975	625	1150	Stanton and Izod specimens.
47	925	1700	Water	425	800	530	985	630	1165	Draw temperatures for tensile, Stanton and Izod specimens.
				425	800	525	975	625	1150	Draw temperatures for endurance specimens. Endurance specimens at heat 15 minutes; all others 45 minutes.
				425	800	530	985	630	1165	Draw temperatures for tensile, Stanton and Izod specimens. Endurance specimens at heat 15 minutes.
48	825	1515	Oil	425	800	525	975	620	1150	Draw temperatures for endurance specimens.
										Special tests: Annealed, 825° C. (1575° F.) furnace cooled, normalized, 900° C. (1650° F.) air-cooled. Frames on endurance specimens only.
49	925	1700	Oil	425	800	530	985	630	1165	Draw temperatures for tensile, Stanton and Izod specimens.
				425	800	520	965	625	1150	Draw temperatures for endurance specimens.
50	815	1500	Oil	425	800	525	975	625	1150	Treatment for tensile, Stanton and Izod specimens, at heat 45 minutes.
	850	1560	Oil	425	800	520	965	625	1150	Treatment for endurance specimens, all except endurance specimens first normalized, 900° C. (1650° F.) in air. Frames on endurance specimens only.
51	...	....	......	...	...	...	...	...	....	Not tested.
52	810	1490	Oil	420	790	525	975	625	1150	
53	870	1600	Water	360	680	420	790	...	....	At heat 6 minutes.
54	870	1600	Water	360	680	420	790	...	....	First normalized 875° C. (1600° F.) in air, at heat for quenching 11 minutes.
55	850	1560	Oil	475	885	575	1065	...	....	One lot annealed 850° C. (1560° F.) 15 minutes, furnace cooled. All others, including endurance specimens, normalized in ¾ inch round, 900° C. (1650° F.) (at heat 15 minutes), air-cooled before heat-treatment. At heat for quenching 20 minutes.
56	...	....	......	...	...	...	...	...	....	Not tested.
57	900	1650	Oil	425	800	525	975	625	1150	Normalized lot, ¾ inch round, 915° C. (1680° F.), air, at heat 45 minutes. Rest not normalized before heat-treatment. Heat treated in 1/16 inch over-size.

Appendix B.

Test-Pieces and Methods of Testing Used, with Special Attention to Endurance Testing.

Tensile Test

The tensile test-piece was the standard 2 inch length, .505 inch diameter, ground to size.

The ends were not threaded but were held in split sleeves. The split sleeves were threaded onto the ends of ball and socket holders. The sleeves were held in place by a snugly fitting steel collar. This gives the central pull of a threaded test-piece held in ball and socket holders without requiring threading the piece itself.

The specimens were broken on an Olsen 100,000 pound three-screw machine at Sibley College, Cornell University. This was driven at a slow pulling rate, about 0.04 inch to 0.025 inch per minute in all tests, both above and below the yield point. The breaking load was usually recorded as well as the maximum load.

Yield points were taken in the earlier tests with a "scissors extensometer." This instrument has a pair of spring clips holding the two legs onto the test-piece over a 2 inch span. The legs are so pivoted together that the outer ends, which actuate an Ames dial, have such a leverage that one Ames dial division corresponds to an extension of 0.001 inch per inch.

This does not give satisfactory determinations of proportional limit, but by attaching a vibrator to overcome sticking of the pivot, gives fair results for yield point.

In later tests a 2 inch Berry strain gage was used, one division of which indicated 0.0001 inch per inch extension, and which could be read much closer by estimating tenths.

Yield points by drop-of-beam are recorded when observed, and give the stress at which the load balanced after stopping the machine as soon as the drop occurred, not the slightly higher value at the drop itself.

Since in many cases no drop of the beam was noted, yield points by extensometer have been given. This is taken as the first detectable deviation from a straight line stress-strain relation when the insensitive scissors extensometer was used, and when the Berry gage was used, by means of

an offset of 2 divisions (corresponding to .0002 inch per inch inelastic extension instead of half that amount as is commonly [292] used in one method of determining "elastic limit") since this particular offset gave practical agreement with the results of the less sensitive scissors instrument and made observations with the two instruments concordant. This figure closely corresponds to the "elastic limit" as commonly determined.

Proportional limit figures, the first detectable deviation from the straight line, (see Fig. 48), are given when the Berry strain gage was used. Of course proportional limit can only be accurately determined by taking, preferably with a mirror type of extensometer, the average extension on three gage lengths 120° apart, to compensate for any bending of the test piece due to lack of a perfectly straight pull. But the ball and socket holders gave a fairly straight pull and the proportional limit figures given are thought to be sufficiently accurate for the comparisons of this work.

On some of the normalized steels the proportional limit figures may be appreciably higher than they would be with the most refined extensometer measurements, but on the quenched and tempered steels the inaccuracy appears negligible.

Reduction of area is recorded in Table 12 both on the basis of the smallest cross section of the broken specimen and on that at the fracture. On specimens which break with a cup and cone fracture the smallest section is at the neck and not at the fracture, and there is a difference of opinion among testing engineers [147] as to whether the reduction should be measured at the neck or at the fracture. In most cases the breaking strength was determined and is computed on the original area.

Cutter's [99] "merit index" is also given. For the calculation of this see p. 61.

Brinell Hardness Tests

Because the endurance specimens, heat-treated in ⅜ inch diameter were so much smaller than the tensile, Stanton and Izod specimens (.505 inch, .500 inch, .450 inch diameters, respectively) a given heat-treatment will not necessarily produce the same results. Also through unavoidable slight differences in speed of quenching, etc., duplicate specimens may vary slightly. It was therefore necessary to make a Brinell hardness test on each specimen in order to detect such differences. The information thus obtained was worth having even though Brinell tests, especially of materials so hard as many of these steels are, are not extremely accurate nor concordant. [212-213]

The Brinell tests were made by grinding a flat area near the end of the test piece, on the side, finishing with a wheel of fine grit and removing scratches with fine emery cloth if the piece was badly scratched after

grinding. The flat area was ground back about an inch and the impression made about ½ inch from the end. The flat area was ground down far enough so that the impression was at least its own diameter distant from the edge, softer specimens being ground down farther than harder ones.

The piece was supported in a V-block, and care was taken that the surface was normal to the axis of load application. The machine is provided with a ball and socket which is designed to insure automatic leveling. A Pittsburg hydraulic Brinell testing machine was used. A load of 3000 kg., maintained for 30 seconds, was applied hydraulically to the 10 mm. ball. The ball was rotated after each test and frequently replaced, particularly when testing the harder steels.

The diameter of the impression was read by a Bausch and Lomb Brinell microscope, Type OM, or in some cases, by projecting the image of the impression, magnified to about 4 inch diameter on the ground glass of a Leitz metallograph camera, measuring it and comparing it with the image of a stage micrometer similarly projected at the same magnification.

The omission of scleroscope hardness readings on such hard steels as were studied in this investigation might be criticized. However, the scleroscopes available did not agree in their readings [62, p. 146] and on pieces of such small mass as the endurance specimens, the difficulties of scleroscopic testing were so great as to make the results of very doubtful value.

Izod Tests

The Izod tests were made by Mr. J. H. Nelson of the Wyman-Gordon Company on specimens furnished in rough ground form after heat-treatment. Round test-pieces .450 inch diameter were used, with the regular Izod notch. The V-notch had an angle of 45° and 0.01 inch radius at the base of the notch. In most cases four tests were made on each specimen, successive notches being placed 90° apart on the circumference. The average figure only is given unless the results were not concordant. Duplicate tests were in general very concordant. An American made, 120 foot pound Izod machine was used.

Stanton Tests

The Stanton tests, also made by Mr. Nelson, were made on a .500 inch diameter test piece about 6 inches long, supported on a 4½ inch span (between adjacent edges of supports) and having, midway between the supports a flat bottomed groove .05 inch wide x .05 inch deep, making the reduced diameter at the base of the notch .400 inch.

The standard tup which was used, weighs about 5 pounds. The height of fall of the tup was kept constant at 2 inches and the speed was

the usual 100 blows per minute. The bar was turned 180° between blows, being hit first on one side and then on the other.

Only the one weight of tup and one height of fall were used. Tests in which the energy of the blow is varied would have been desirable, but in most cases there was insufficient stock to allow this.

Two specimens were generally tested, and as the figures agreed quite well, the average only is given unless the results were not concordant.

It is necessary to note, in comparing published Izod and Stanton tests whether exactly the same form of specimen was used. Various dimensions and notches are used in Izod testing and the results can only be approximately corrected to allow for differences in the test pieces. Izod tests herein are reported in foot pounds observed, not being reduced to foot pounds per square inch.

In the Stanton test, a V-notch .04 inch deep is sometimes used which makes the diameter of the test section at the base of the notch .420 inch and increases the area at the base of the notch about 10 per cent. over that with the notch .05 inch deep.

Endurance Tests

The endurance tests were made on two Upton-Lewis endurance testing machines at Sibley College, Cornell University. The principle of the machine involves, in its simplest form, a crank arm whose throw can be varied by moving it in a slot on a rotating head. In the middle of the arm the test-piece is so gripped by jaws as to become a part of the arm. At the other end of the arm is a cross-head whose motion is resisted by calibrated springs at each side of the crosshead. As the eccentric end of the arm oscillates, the test-piece is bent back and forth. From the dimensions of the test-piece, the length of the lever arms, the calibration of the springs and amplitude of cross head motion (*i.e.*, the compression of the springs) the maximum fiber stress on the test piece can be computed. The springs are set as nearly as possible so that the specimen receives equal stress in tension and compression, *i.e.*, the stress cycle is completely reversed. The equality of tension and compression is probably not as good as in a rotary type machine.

In the older form of the machine (Plate 17) used in these tests, the crank arm is pivoted, but the principle is the same, although the pivot is a source of trouble that seriously impairs the usefulness of the older type. If the pivot is too loose a lost-motion is introduced which makes accurate measurement of stress impossible, while if too tight, it introduces appreciable friction which causes the crosshead motion to be less than it should be and hence indicates a lower stress in the specimen than the true one.

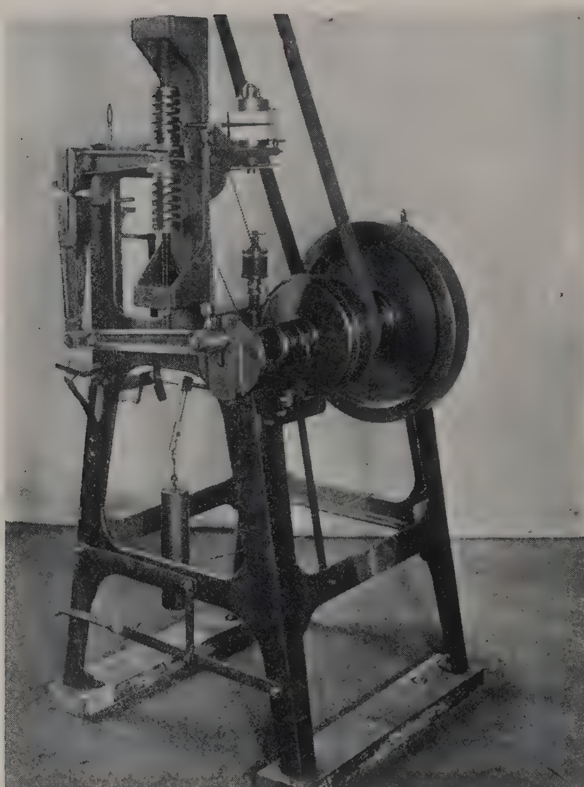


PLATE 17.—Upton-Lewis Endurance Testing Machine.

The pencil-record device shown here was replaced by an Ames dial for measurement of amplitude of cross-head motion.

The Upton-Lewis test has heretofore usually been made on a flat test piece, sometimes necked down on the thinner sides, which is gripped in the jaws by hardened steel liners. There is no reason why a round test-piece should not serve as well.

Some of the steels it was desired to test were available only in ¾ inch or 1 inch round bar, and it was not considered good rolling practice to attempt to re-roll these to flat bars such as are usually used on the Upton-Lewis test. Hence the stock for Upton-Lewis tests was re-rolled to ⅜ inch round.

The liners used for flat specimens were replaced by others, each with a half-round groove, closely fitting the diameter of the test-piece.

Several different sets of springs were provided in order to obtain suitable deflections for the different ranges of fiber stresses desired.

The Upton-Lewis machines were originally provided with a mechanism by which the amplitude of the crosshead was multiplied and recorded on a paper roll by a pencil arm. The height of the pencil record was measured and from this the amplitude of the crosshead and hence the stress in the specimen calculated. This is quite satisfactory for use of the Upton-Lewis machine as a "toughness tester" at stresses well above the elastic limit, when the test piece is broken after a few thousand alternations, but at the lower stresses and lesser heights of the pencil record of a true endurance test the errors due to lost-motion and friction in the pencil mechanism and to dulling of the pencil point, and the difficulty of exact measurement of the height of the record, were so great that after a preliminary series of tests the use of the pencil record as a means of stress measurement was discarded. Ames dials graduated in 1/1000 inch and readable to 1/10000 inch by estimation of tenths were mounted so as to read the amplitude of the motion of crosshead directly.

The dial reading or the pencil record height of crosshead motion is greater when the machine is running at full speed than when it is slowly turned over by hand. Since the amplitude of the crosshead motion under running conditions is obviously the figure to use in calculation of the fiber stress in the piece during actual test, the hand readings were taken only to obtain the proper setting of the crankarm and all calculations were made from the running readings. Readings were taken at intervals throughout the life of the piece.

In this work a stress range of equal tensile and compressive stresses was always maintained as nearly as possible. The free test piece length between jaws was set by a gage at .500 inch for un-necked and .667 inch for necked test pieces.

The number of alternations before fracture was recorded by a revolution counter. When the specimen broke the revolution counter and the driving motor were stopped by automatic devices. The machines were

run at speeds of 480 to 680 R. P. M., the usual speed being 525. Within these limits no differences were found in endurance limit due to differences in speed of testing.

It was at first thought that it would not be necessary, in order to get comparative results, to reduce the diameter of the test pieces at the breaking section.

Because the loading in the free length of the test-piece between the jaws is almost one of uniform bending (about 4 per cent. less at the lower jaw than at the upper with a ½ inch free length) when an un-necked test-piece is used, this form would bring more material under stress and, from one point of view, be a better test piece for that reason. Un-necked test pieces were therefore used at the start, following the practice of Professor Upton and others in toughness tests, *i.e.*, those made above the elastic limit of the steel. (214)

While the un-necked test-piece may be fairly satisfactory for toughness tests, it is far from satisfactory for endurance tests. A large number of tests were made with un-necked specimens, much time lost thereby and much stock used, without obtaining any results of real value. It will be desirable to describe some of these early tests and to consider their results in order to show the necessity for the use of a different form of test-piece, such as was finally adopted.

When these tests were started, knowledge of endurance testing was decidedly chaotic and test-pieces and methods of testing were far from standardized.

Tests on Un-necked Bars

The un-necked specimens were ground to size, and longitudinally polished until all circumferential scratches were removed because the effect of surface notches, scratches, flaws or inclusions cannot be neglected in any consideration of endurance testing.

By study of celluloid under polarized light Coker (207, 215) shows that the local stress at an open round hole is three times the calculated average stress and at a plugged hole, twice. Inglis (216) gives a mathematical analysis of the stresses about an elliptical hole showing that with an ellipse having its major axis three times its minor axis and having its minor axis in line with the stress, the stress at the apex is seven times the calculated average. As the angle of the major axis to the line of stress changes the excess stress decreases, being 4⅓ times the calculated average at an angle of 45°, and when the major axis is in line with the stress, the increase of stress is zero.

As the hole becomes longer and thinner so that the major axis is 100 times the minor axis, the local stress rises to 201 times the calculated average if the minor axis is in line with the stress, and when the major

axis is 1,000 times the minor, *i.e.,* as we approach a long straight crack, the local stress is 2,001 times the calculated, if the apex of the crack is normal to the stress. An infinitely sharp crack has infinite stress at the apex. But if this crack is in line with the stress instead of across it has no effect. The increase of stress is then nil.(10, p. 295) Jenkins (162, p. 12) also shows this, and gives a comprehensive discussion of the whole subject of external "stress-raisers." Hence circumferential scratches on the surface of a rotary bending test-piece (whose surface only gets the maximum stress) may have a fatal effect while longitudinal scratches are without effect. In torsion the stress-raising effect of a scratch is only half that of a similar one at right angles to the load in tension, but the scratch is, in torsion, equally bad when at any angle. (162)

In the discussion of Inglis' paper, Strohmeyer remarked that real cracks and mathematical cracks were different. Cracks or sharp corners are dangerous enough and do raise the stress, but they do not have as bad an effect as the mathematics would predict.(304)

Griffith (217) considers this question and points out that according to the mathematical theory of elasticity the stress-raising power of a scratch is dependent on the radius of curvature of the apex of the notch and not on its depth, *i.e.,* a scratch 1/100 inch deep and one 1/10000 inch deep should have the same effect, which is not in accord with experimental facts.

At any rate it appears necessary, in order to avoid local increase of stress, due to scratches, to prepare specimens for endurance test under reversed bending so that all circumferential scratches are removed and so that the longitudinal scratches are not deep. In preparing the necked specimens finally used, the pieces were first ground cylindrical and then necked down on a centerless grinder by a formed grinding wheel. They were then held by hand against a rotating lap. The lap consisted of a 2 inch diameter wooden cylinder covered with garnet cloth or emery paper. The lap fitted the neck which had a 1 inch radius. The specimen was slowly turned on its axis and from time to time turned end for end. The finest grit of "Three M-Ite" garnet cloth was used until all the circumferential grinding marks were found to be removed when the bar was inspected under a x 10 hand magnifier or a Brinell microscope. The bar was then polished successively on Hubert emery paper No. 1, No. 0, No. 00, and finally on No. 000. It is doubtful whether much is gained by continuing the polishing so far, but it was always done because as the finish became smoother, tiny circumferential scratches that were formerly not visible under the lens often became visible, and in such cases polishing was continued until no trace of a circumferential scratch was to be found on the middle third of the necked portion. Rouge finishing was avoided because of the alleged tendency of this polishing material to induce the

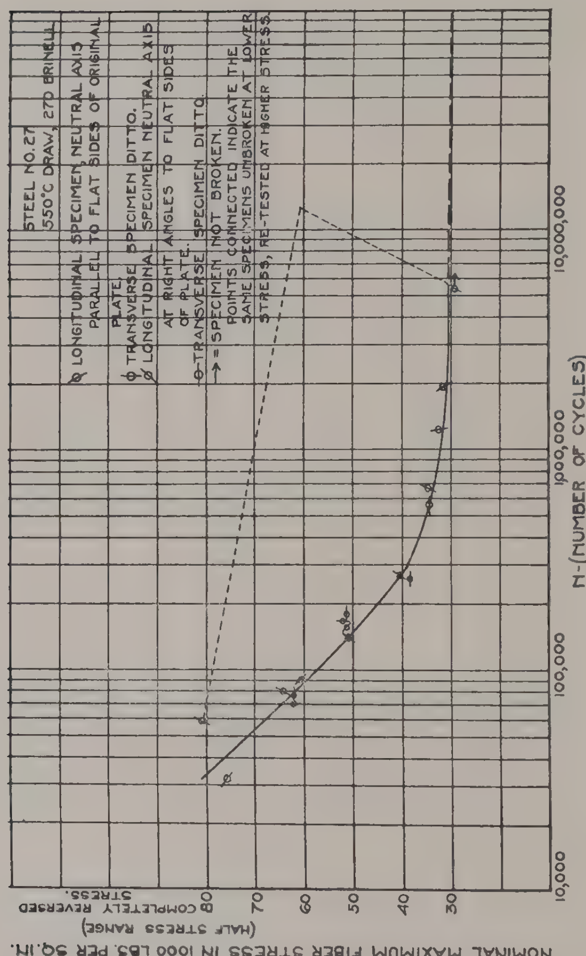


FIG. 60.—Endurance curves for un-necked specimens, giving erroneous results.

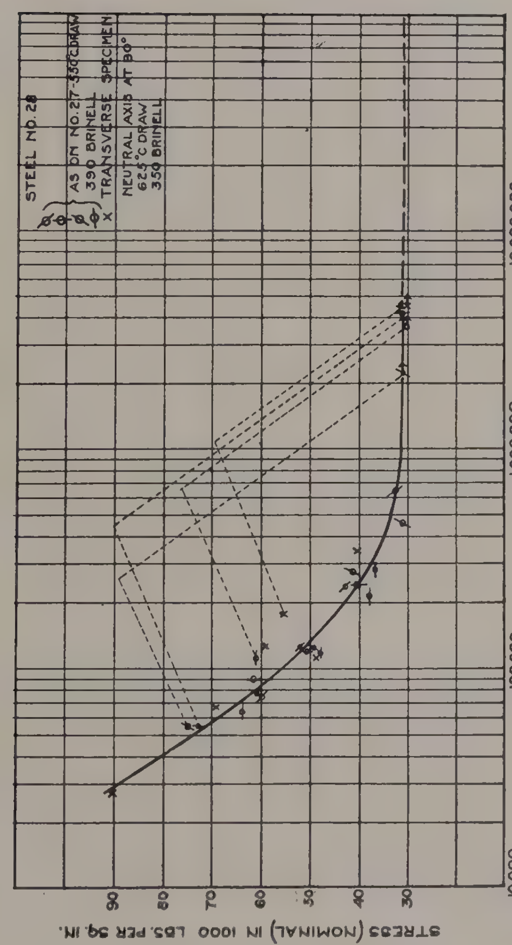


FIG. 61.—Endurance curves for un-necked specimens, giving erroneous results.

formation of a flowed or worked surface layer. The final finish was almost a mirror finish, but tiny longitudinal scratches were still visible. After the final polishing the diameter at the minimum section was carefully measured with a micrometer having a rounded spindle and anvil, care being taken to avoid marring the finish of the specimen. The specimens were then oiled to prevent rusting. They were again examined with the hand magnifier just before use.

This polishing to complete elimination of circumferential scratches was adopted from the start of the endurance work, whether on necked or un-necked specimens. Recent publication of results of endurance tests indicates that no particular finish has yet been accepted as standard.

Plate 18-b shows the finish of a necked specimen at 100 diameters.

Figs. 60 to 63 for un-necked specimens of steels No. 27 to 30 are for both longitudinal and transverse specimens from chromium, chromium-molybdenum and chromium-vanadium steels rolled, without any cross rolling, from an ingot 6 inches wide by 3 inches thick to a plate 6 inches wide by 0.6 inch thick, all the steels being given the same heat-treatment. Specimens were tested both with the piece so placed in the testing machine that the direction of rolling was in line with, and across the line of maximum stress. Although the Brinell hardness of these steels varied from 270 to 390, the curves do not differentiate among the steels. All the steels show an endurance limit at a nominal stress of about 30,000 pounds per square inch. No consistent difference can be noted between specimens cut longitudinally or transversely. In plotting these results the same conventions are used as in the case of the necked specimens, see p. 144.

Even on the soft steels of 165 to 190 Brinell hardness shown in Fig. 64 for steels Nos. 53 and 54 the indicated endurance limit is still about 30,000 pounds per square inch although the life at the high stress end of the curve is not so long as with the harder steels of Figs. 60-63. With the soft normalized steels of 130 Brinell hardness shown in Fig. 64 the indicated endurance limit is reduced to about 24,000 pounds per square inch and the life at high stresses falls still lower. With very hard steels, the indicated endurance limit was higher as is shown in Fig. 65, in which are plotted the authors' curve for a test of un-necked round specimens of a steel of about 220,000 pounds per square inch tensile strength and about 400 Brinell hardness (Steel No. 10, draw 1), early Upton-Lewis tests by Moore and Putnam [218] on a tempered spring steel of 224,000 pounds per square inch tensile strength, and an average curve plotted from the recent data from Lewton [133] on Upton-Lewis tests of spring steel of about 400 Brinell hardness.

Moore and Putnam used a flat specimen ¾ inch or 1 inch wide reduced to 0.06 inch in the test section by a fillet of not over ⅛ inch radius. Lew-

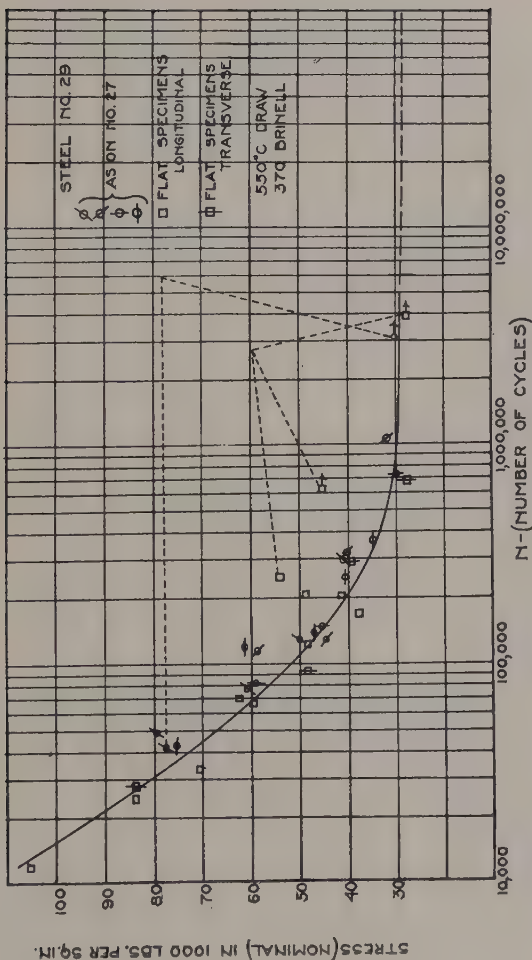


FIG. 62.—Endurance curves for un-necked specimens, giving erroneous results.

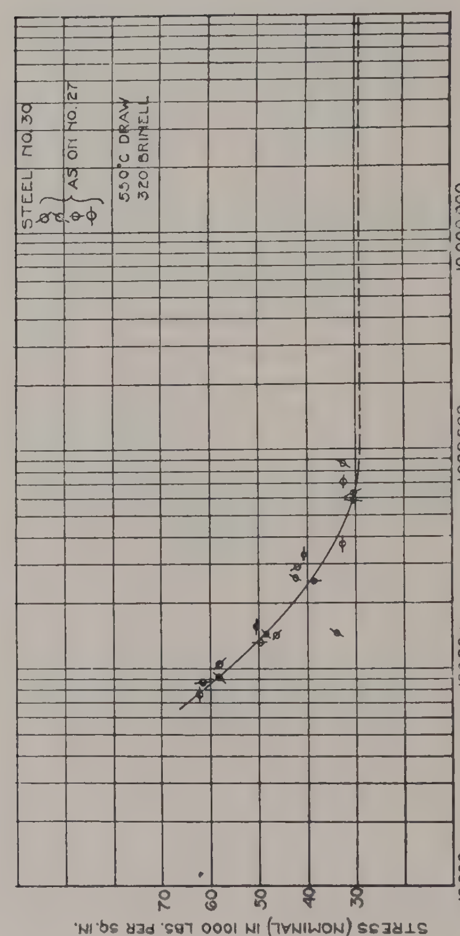


FIG. 63.—**Endurance curves for un-necked specimens, giving erroneous results.**

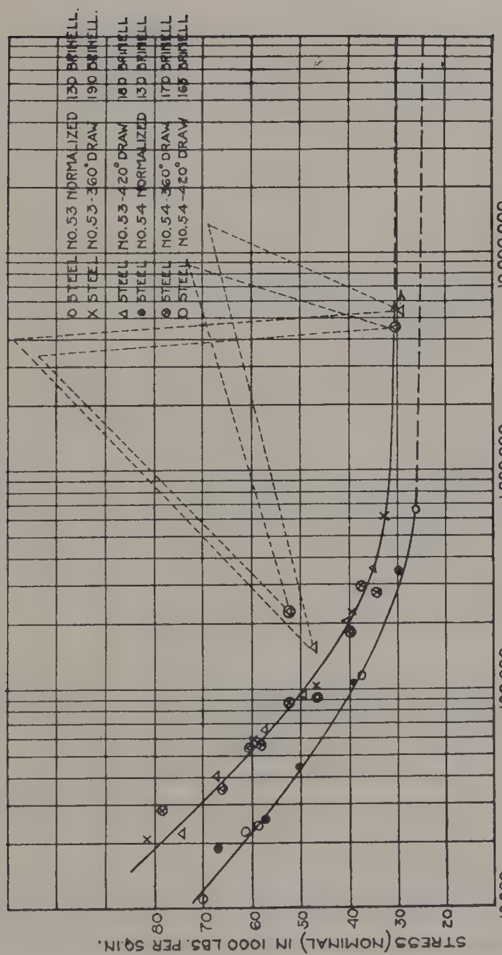


FIG. 64.—Endurance curves on un-necked specimens, giving erroneous results.

ton used flat test-pieces not necked or reduced. The results on the three types of test-pieces are seen to be nearly identical on similar material.

In a discussion of the endurance tests of Moore and Kommers, and of several German workers, Stribeck [220] cites tests made by Lasche on rectangular test-pieces, which show endurance limits far below those to be expected from Moore's latest results. While the exact conditions of testing and form of test-piece are not clearly given, Stribeck ascribes the

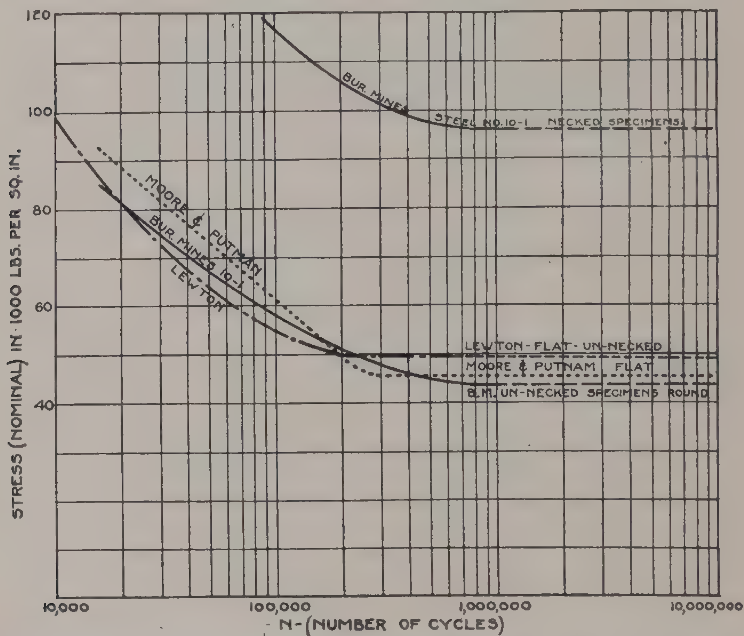


FIG. 65.—Endurance curves on un-necked specimens, from results of various investigators, giving erroneous results, compared with curve for necked specimens. All four curves are for steels of approximately the same Brinell hardness.

discrepancy to gripping the piece so as to set up local excess stress. These test-pieces were apparently not necked.

The tensile strengths of five lots of Siemens-Martin steel, 5 per cent. nickel or 25 per cent. nickel tested by Lasche ran between 78,000 and 114,000 pounds per square inch but the endurance limits varied only from a nominal stress of 27,000 pounds per square inch to one of 34,000 pounds per square inch.

It will be noted that this nominal endurance limit, almost constant for steels of different strength, is very close to the nominal figure found in the authors' tests of un-necked specimens, for steels of different strength.

Moore and Gehrig [219] used a flat test piece reduced in the breaking

section by fillets of small radius and state that this form doubtless caused some irregularity of stress at the shoulders, but that this was less than that due to the heavy localized stresses where the jaws grip the test piece in an un-necked specimen.

That such localized stresses were present in the authors' early tests was evident from the fact that while about 95 per cent. of the un-necked specimens broke at the upper jaws, where the calculated stress is highest, the other 5 per cent. broke at the lower jaw, where the calculated stress is some 4 per cent. lower. The un-necked specimens never broke between the jaws. Moreover, the edges of the semicircular grooves in the hardened liners gripping the specimen, wore down slowly and the liners required frequent replacement so that the localized stress would vary with the condition of the liners. To check up on the question of localized stress a set of specimens was machined from steel No. 49 by milling the bar to ½ inch thick, heat treating it (925° C. (1700° F.), oil; 525° C. (975° F.) draw) and then machining a .36 inch diameter test length, the radius between the reduced section and the body of the bar being made as small as possible. The test length was then polished longitudinally as well as could be done with a specimen of such shape. This gave a specimen with a test length integral with the bar which corresponded to the un-necked round specimens gripped in the liners.

The results of early tests on round specimens at the same heat-treatment are compared with those from the square shouldered specimen in Fig. 66. It is quite plain that the round un-necked specimen held in the liners is as poor as the specimen with square shoulders, which is obviously of very bad design. Later results on necked specimens are also included in the figure.

It was plainly necessary to go to a test-piece which was more nearly free from localized stresses than either the un-necked piece or the Moore and Gehrig specimen.

There seemed to be no reason why the Upton-Lewis machine should not give the same results as the rotary bending machines if a test-piece of proper form was used. By using a piece of the same geometrical proportions as the one finally worked out by Moore for his rotary bending tests, this was found to be the case, and a .35 inch diameter test-piece necked down to .23 inch on a 1 inch radius was adopted. No wear of the liners was detected after the necked test-pieces were used. This gives the same ratio of cross sectional area at shank and at the minimum section as in Moore's .40 inch-.27 inch Farmer machine test-pieces, or his .625 inch-.43 inch test-pieces for his later tests on combined tensile and bending stresses. Moore found a 1 inch radius almost as good as the 9.85 inch radius on the Farmer test-pieces, giving results only 1 or 2 per cent. low. He now uses the 1 inch radius on the combined tensile and bending bars.

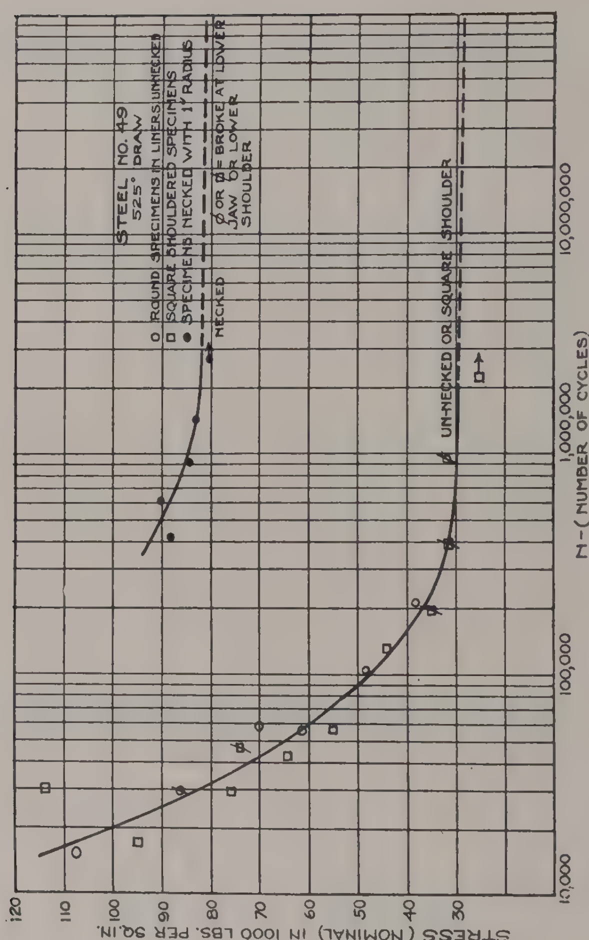
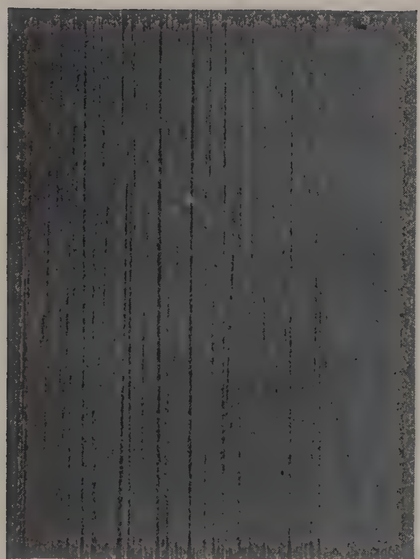


FIG. 66.—Endurance curves for the same steel. Lower curve for un-necked or square shoulder bars, giving erroneous results. Upper curve for necked bars.

18a

18a—Actual size

Necked (round) specimens for Upton-Lewis endurance test.



18b

× 100.

Surface finish at point of minimum section; necked, round endurance specimen. The abrasive scratches are parallel to the long axis of the specimen.

PLATE 18.—Shape and surface finish of round, necked, endurance specimens.

Two necks were usually made on each 6 inch specimen. Plate 18-a shows the type of bar used by the authors.

The necessity for proper necking of the test piece and for proper surface finish can scarcely be over-estimated. The Upton-Lewis machine is in considerable use as a "toughness tester" when these points may perhaps not be essential, but the time spent on true endurance tests without attention to these points is worse than wasted because the results of the tests often get into the literature with nothing to show that they were made under improper conditions and the false data are worse than none.

Choice of Number of Cycles for Test

A suitable test piece form having been selected, the next question is how many stress cycles shall be run on specimens that do not break. It was impossible to test all the steels it was desired to test with only two endurance machines and impossible to run many tests into the tens or hundreds of million of cycles.

Until recently it was in doubt whether or not there exists a real endurance limit for wrought ferrous metals, but the prominent workers [47, 118, 162, 173, 174, 179] in the fatigue field are now in substantial agreement on this question.

They agree that with a test piece suitably reduced in section and polished there is a fairly definite stress, as calculated by the ordinary formulae of mechanics, above which stress the specimen will break fairly promptly, but just below which the specimen will withstand a million, ten million, a hundred million or even (by some actual tests) a billion cycles without breaking.

This applies only to wrought, ferrous metals. Cast metals and non-ferrous metals in general may or may not possess an endurance limit.[233, 312] It will take much more work on these materials before the theory and practice of endurance testing of these materials can emerge from its present chaotic state.

For steel, the existence of this definite stress at the endurance limit is made still more certain by the fact that after stressing above it, the specimen is damaged so as to show a lower resistance to repeated stress of smaller magnitude; and after stressing, just below it, it shows greater resistance to repeated stress of greater magnitude. The steel is damaged by overstressing and improved by understressing. At the endurance limit, for virgin material, these tendencies balance.

When the stress (S) and number of cycles (N) are plotted on ordinary co-ordinates or on logarithmic or semilogarithmic co-ordinates (in the last case N being logarithmically plotted), there is a "knee" or break, in the curve and the position of this "knee" locates the stress corresponding

to the endurance limit. Moore [173] plots his curves with two straight branches meeting sharply at the "knee."

The writers have taken the liberty, in re-plotting data from Moore or other workers, of drawing the S-log N curve with a rounded "knee", and, moreover, to draw the low stress (long life) end of the curve at a very slight angle instead of exactly parallel to the N-axis. It is admitted that at an absolute endurance limit the curve would be parallel in theory, and it may be true in practice. But in the cases in which the course of the curve can be traced by many consistent points, curves like the upper one in Fig. 67, from Moore's data, are obtained. It seems conservative to avoid the assumption that the curve becomes absolutely parallel to the N-axis, *i.e.*, that a bar tested just below what is taken as the endurance limit has infinite life, because an infinite life test cannot be made. Moreover, in practice no steel nor specimen can be assumed to be, nor is, perfect in finish nor in freedom from non-metallic inclusions. Local stress-raisers thus being present, nuclei for failure might sometimes develop about them at an average stress very slightly lower than the endurance limit indicated by tests of finite duration.

With this concession to absolute exactitude and to our experimental limitations, we may then point out that with so slight a slope in the curve it is a matter of no practical moment whether the curve is parallel or sloping, because any factor of safety at all will insure a life satisfactory for engineering purposes. The piece would rust away or the machine in which it was used would become worn or obsolete before the piece would fail by fatigue. This assumes that all pieces to which the factor of safety is to be applied are as free from local stress-raisers and have the same endurance properties as the specimens tested. Since this may not be the case, a large, rather than a small factor of safety is really required.

The engineering endurance limit, on which to base the factor of safety and the relationship between the endurance limits for reversed bending, reversed torsion, and reversed axial stress, may then be taken as the stress at which the flat part of the plot begins to curve, just as one takes the proportional limit from a static tensile stress-strain diagram.

The question then is, to how many cycles shall a reversed stress endurance test be carried unbroken to insure passing the "knee" of the curve, or to be so close to the knee that the difference in stress will be immaterial from the engineering point of view?

In studying the method of endurance testing on a new class of material many specimens and many cycles must be used, but in routine testing on a class of material which has been thoroughly explored, we may stop at the number of cycles which has been previously shown to be adequate.

A study of McAdam's plots [47] shows that in 85 per cent. of the

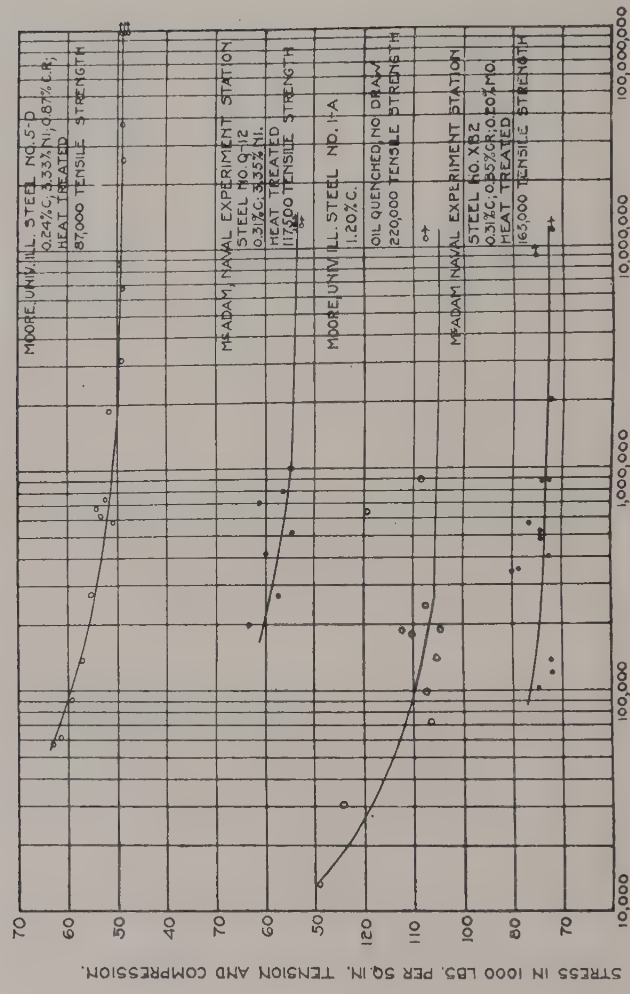


FIG. 67.—Endurance curves, from data of Moore and McAdam, showing form of typical curves, and scatter of points.

cases the same figure for endurance limit would be found if the tests were stopped at 1 million instead of 10 million, while in 15 per cent. the stress would be about 2000 pounds per square inch or less above the value found with 10 million as the criterion. A similar study of Moore's data [172-174] shows that on the Farmer test 78 per cent. give the same figure on tests to 1 million cycles only, while in 22 per cent. the stress for 1 million is about 2000 pounds per square inch or less above the stress at 10 or 100 million cycles. Moreover, the steels which require carrying tests beyond 1 million are, in both cases, always low carbon or annealed steel, *i.e.*, soft steels. Heat-treated alloy steels, in the tests of both investigators, always show the endurance limit by tests to a million cycles, if a reasonable number of specimens are tested so as to minimize the effect of accidental variations.

In Moore's work with the Upton-Lewis machine, he ran tests only to 2 million cycles and always found a "knee" in the curve, even on the softer steels, at or below 1 million cycles.

Variation in Cycles Required with Hardness of Steel

The harder steels seem to give a sharper "knee" in the curve and to give it at a lower number of cycles, so that, in general, the relationship in Fig. 68 seems to be a fairly accurate first approximation. McAdam, [221] shows a similar family of curves plotted on ordinary co-ordinates, at high stresses and very low numbers of cycles, for alternating torsion tests of several classes of steels.

While the two sets of curves cannot be directly compared, both show a much steeper slope at the highest stress, shortest life end of the curve in the case of hard steels than of soft ones. While the exact number of cycles required to locate the endurance limit seems to vary somewhat with the test-piece and the testing machine chosen and possibly with the speed, in general it seems that on a steel of 200,000 pounds per square inch tensile strength the "knee" in the curve appears at about half a million cycles, while in one of 50,000 pounds per square inch tensile strength it appears at about 5 million cycles.

Too little work has been done at speeds much above 2000 reversals per minute to allow prediction of what will occur at higher speeds.

While 1 to 5 million cycles thus appears adequate for steel, the case is very different with non-ferrous alloys and the short-cut used must very definitely be restricted to *wrought, ferrous, alloys only,* at least until definite proof of its applicability to other alloys is available.

It should also be very definitely pointed out that the recent work of Moore [174] at the University of Illinois shows that the endurance limit found by rotary or reversed bending test is higher than that found on reversed axial loading, *i.e.*, in direct tension and compression, where the

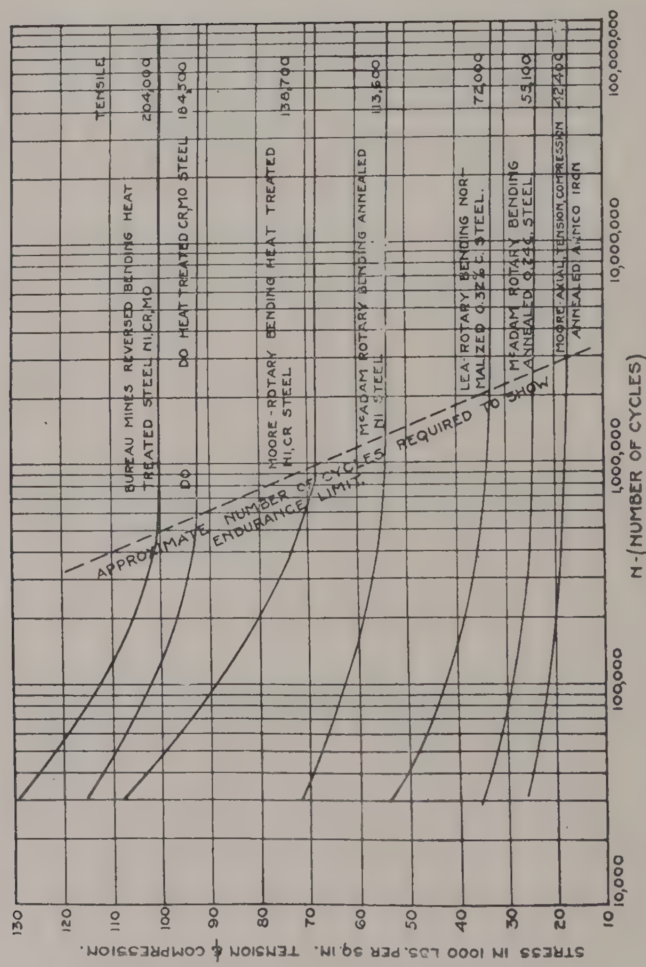


FIG. 68.—Endurance curves, from data of different investigators, showing location of the knee of the curve for steels of different tensile strength.

whole cross section of the test piece is equally stressed instead of having only the surface stressed to the maximum. In the comparisons so far made by Moore, the axial endurance limit is only about 63 per cent. of that in rotary bending. This must be taken into account, and the endurance limit in bending must not be used as the basis for design of a part under reversed axial load.

In this report only reversed bending tests are dealt with. No axial tests were made.

Lack of Perfect Accuracy in Endurance Tests

The S-N endurance curve has such a very slight slope at stresses below that giving a life of 10 million cycles that engineering design based on the endurance limit at 10 million cycles should be satisfactory. In fact, in the most carefully made endurance tests there is usually a greater variation between the stresses on two duplicate specimens that happen to give approximately the same life than between the stresses calculated for endurance limits on the basis of a series of specimens tested only to 1 million cycles and of another series tested to 100 million. On account of the difficulties in testing due to lack of alignment of bearings, lack of absolute straightness of specimens, vibration, inaccuracies in spring calibration, etc., the absolute value of the stress at the endurance limit in any type of machine is generally in doubt by as much as the stress differences at 1 million and 100 million cycles. Indeed, a 5 per cent. variation between duplicate tests of tensile strength or proportional limit, which are stress figures, is accepted in ordinary testing without any comment. In an endurance test, however, such a difference in stress means a vast difference in life. In the upper curve of Fig. 68, for instance, the life at 100,000 pounds per square inch is 2 million or more; at 105,000 pounds, 250,000; and at 110,000 pounds, 125,000.

In view of these facts it is obvious that engineering design based on endurance limit tests must still be made with a factor of safety of such magnitude that the difference between endurance limits at 1 million and 100 million cycles may be neglected. For metallurgical comparisons between different steels one million cycles for hard heat-treated steels, like spring steels, and 2 to 5 million cycles for softer steels, such as low carbon or annealed steels, should be ample. For special purposes, it may still be necessary to run to 100 million cycles.

Use of the Strengthening Effect of Understressing

Nevertheless, the authors have not felt safe in stopping the tests when a hard steel lasts 1 million or a softer steel 2 or 5 million cycles unbroken. But instead of continuing the test at the original stress, use has been made

of the phenomenon noted in the early work of the authors and since corroborated by various workers (47, 172-174, 179, 222-224) on endurance, by which a specimen tested a little below its endurance limit is strengthened by understressing, and on testing again at a higher stress is found to have an increased life over that of a virgin specimen originally tested at the higher stress. Lea (179) discusses this question clearly and thoroughly. Strengthening by understressing seems to be intimately connected with the phenomenon of the reduction of elastic hysteresis and raising of the elastic limit by cyclic stressing, which has been studied by various investigators.(10, p. 143; 162, 168, 175, 179, 225-226, 290)

If, then, a specimen is tested slightly below its endurance limit, it is not damaged but improved, while one tested above its endurance limit probably has begun to show incipient failure, and on re-test at a still higher stress, it should fail earlier than a virgin specimen.

The practice of the authors on the hard, heat-treated steels chiefly studied, has been to run the tests until a stress was found at which the specimen would withstand about 1¼ million cycles unbroken, and, without removing the specimen from the machine, to raise the stress at once about 10 per cent. and continue the test. All tests were continuous, the machines being stopped only to raise the stress in cases where it was required, a matter of about a minute.

If at the higher stress the specimen shows a life equal to (or greater than, as is usually the case) the life of a virgin specimen it is considered that the specimen was not damaged by the first test and would have lasted very much longer at the original stress. If it shows a life lower than that of a virgin specimen (which occurs extremely rarely) it is considered that the specimen was damaged in the original test and that a somewhat lower stress must be tried on a new specimen to make sure of locating the endurance limit. On the few very soft steels tested the number of cycles at the original stress was increased to about 2½ million. By this method of increasing the stress it is believed that the results are as dependable as if the tests had been carried to 10 million cycles at the original stress, while the saving in time is obvious.

In plotting the data attention is paid only to the points representing initial stresses. Tests at raised stresses are of use for confirmation of the assumption that an unbroken specimen at the initial stress would have lasted still longer. The contrary procedure, as suggested by Batson and Hyde, (168) is certainly wrong.

Use of Proportionality of Brinell Hardness and Endurance Limit

Another time-saver is the use of the proportionality between endurance limit and tensile strength (or Brinell hardness). For tests in rotary or

reversed bending, on specimens necked down with a radius large enough to avoid local excess stress at the fillet, recent investigators agree in finding that the endurance limit for steel is approximately 40 to 50 per cent. of the static tensile strength, whether the steel be a very soft one or a moderately hard one. Even air-hardening steels drawn at low temperatures, in which the endurance limit is above the static proportional limit, follow this empirical rule fairly closely.

If, then, we divide the tensile strength by 2 or multiply the Brinell hardness number by 250, we get an empirical value for the probable endurance limit. This factor corresponds to one of Brinell $\times$ 500 = tensile strength [227] and while this factor is not an exact one,[228] yet a study of Abbot's data shows that from a Brinell hardness of 200 to 400 this factor gives a curve lying within the "scatter" of his plotted points.

The first stress in harder steels can be taken from the curve of Fig. 32. If the first endurance test run at this stress fails at say ½ million cycles a stress lower by about 2,000 pounds is chosen for the next test. If it should fail at say 200,000 cycles a stress 5,000 pounds lower would be used next. If the first bar stands 1½ million at the chosen stress and another 1½ million at a 10 per cent higher stress, breaking in say 200,000 cycles on a third test at a stress 20 per cent. above the original, then for the next specimen the stress would be increased by 5,000 pounds over the original.

Four specimens, two unbroken at 1½ million cycles and two broken at 100,000 to 800,000 cycles at stresses thus chosen, will often serve to fix the endurance limit within about 2,000 pounds per square inch which variation in stress is considered about the limit of accuracy in this work, due to inaccuracies in endurance testing, which have been previously discussed.

The two Upton-Lewis machines were usually set up, one with a stronger set of springs than the other, on which the steels of higher tensile strength were tested, while the one with the weaker springs was used for the weaker steels, in order to keep the deflections of the Ames dial as large as possible and make for accurate stress calculation.

Some of the steels of intermediate tensile strengths were tested on both machines, data so obtained being as consistent as when one machine only was used.

The fracture should occur at, or a few hundredths of an inch above, the minimum section of the necked specimen, since this is the point of maximum stress. The location of the fracture was always recorded, and specimens breaking appreciably above or below the minimum section were noted in plotting, for such a specimen broke at a point actually at a lower stress than that with which the specimen is credited, while the middle of the piece was still unbroken at the stress calculated. Most other

investigators find that a considerable proportion of their specimens fail at some point other than at that of maximum stress. Few, however, take account of this in plotting the results of their test.

The Question of Completely Reversed Stress

Inasmuch as it is difficult to set the springs in the Upton-Lewis machine so as to be certain that the stresses in tension and compression are exactly equal, it is necessary to consider the effect of slight deviation from completely reversed stress.

The tests of Moore and Jasper [172, p. 67] in which steels were subjected to steady tension plus reversed bending, thus giving repeated stress not completely reversed, indicate that a deviation of 20 per cent. from completely reversed stress has practically no effect on the endurance range save in the case of the softest steel tested, in which 10 per cent. deviation caused a slight lowering of the range.

From his tests on incomplete reversal of stress in repeated torsion, McAdam [47] concludes that as long as the maximum stress is within the static elastic limit the effect of unbalanced reversed stress is very slight.

It therefore appears probable that any slight deviation from equal tension and compressive stress in the authors' Upton-Lewis tests is without detectable effect on the results. Stresses plotted are, strictly speaking, half the stress range, but clearly approximate to completely reversed, equal, tensile and compressive stresses.

Rise of Temperature Method of Making Endurance Tests

Several investigators have attempted to find shorter methods of determining the endurance limit than the tedious one of running several specimens at different stresses to fracture or until they have withstood a million or more cycles unbroken.

Methods so advocated are the change-in-rate-of-deflection test of Gough [229, 308] and Lea [179] and the rise-of-temperature method of Moore [172-174] and co-workers.

Gough's own data [230] on his method applied to copper shows a case in which a virgin specimen gave a certain break in the cyclic stress deflection curve which appeared to check up satisfactorily with life tests. A duplicate specimen after being overstressed gave the same break in the curve, indicating the same endurance limit, but when the specimen was given a life test it failed quite promptly well below the original endurance limit. The accelerated test thus failed to differentiate between virgin and damaged material.[320]

Moore's first data [173] indicated good correlation between his accel-

erated rise-of-temperature test and the endurance limit of steel, but he has since found cases where [174] the specimen would heat up perceptibly at the start, later cooling off and running 100 million cycles unbroken.

The writers [285] attempted to apply the rise-of-temperature test to the round necked Upton-Lewis specimens. The results were not satisfactory, the break in the rise-of-temperature curve coming above the true endurance limit and so irregularly above it that no correction could be made. A round test piece in reversed bending, as in the Upton-Lewis machine, is stressed to the maximum only at two opposite points on the surface instead of at all points of a circumference as is the case with a test piece in rotary bending. The heat evolution on incipient failure is so small in the Upton-Lewis test piece that even more sensitive apparatus than that used by Moore was not capable of locating the endurance limit by this method.[317]

The accelerated tests may give useful information, but though accepted by some testing engineers,[309] they do not yet appear to be developed to the point where they can be confidently accepted as substitutes for endurance tests made by running several specimens, some to fracture and some to millions of cycles without fracture.

McAdam [313] has developed apparatus and methods for accelerated endurance testing which give promise of usefulness, but which have not yet been reported on by other workers.

There are uncertainties and discrepancies enough in the conventional type of test but there is a degree of certainty that a stress at which a specimen of spring steel remains unbroken after a million cycles, or at which one of soft steel is unbroken after 5 million, gives a working basis for engineering design which is so far lacking in the accelerated tests.

For the theory underlying the phenomena of fatigue failure or progressive failure the reader is referred to the publications of Moore [172, 174, 232, 288, 306, 307] and to that source and others [47, 118, 168, 179, 233-245, 303-314, 317-321] for detailed descriptions of the various testing machines. All that has been attempted here is to explain the precautions found necessary in order to use the Upton-Lewis machine for true endurance tests and the most rapid method of getting results reliable enough for the purpose of the work, *i.e.*, determining whether molybdenum steel was superior or inferior to other alloy steels in endurance.

Appendix C.

Composition, Rolling, Heat-Treatment and Test Pieces of Nickel-Silicon Steels.

The essential data on the composition of the nickel-silicon steels are given in Table 16, Chapter 11. Zirconium and cerium segregate in the ingot when the content is appreciable and the analyses of a sample taken from the top of the ingot is given in Table 16 in the line for the top or "A" plate. Since some steel was cropped from the sheet below the point of sampling, the A plate may be slightly lower in zirconium or cerium. Analysis for zirconium and cerium was also made on the bottom of the ingot and this figure has been put in the line for the plate from the bottom of the ingot, the "C" or "D" plate: In the case of I-25, only two plates were obtained, so the "B" plate is from the bottom.

All these steels, as well as those previously discussed, carried about 0.03 per cent. to 0.04 per cent. copper from the raw materials. I-7, I-18, and I-19 contained 0.01 per cent. and I-20 and I-25, 0.02 per cent. chromium, from the zirconium alloys used which had been made in furnaces previously used for making ferro-chromium.

The phosphorus content of the nickel-silicon series varied from 0.01 to 0.02 per cent. averaging 0.015 per cent.

The sulfur content averaged 0.03 per cent. This was determined by the evolution method on steels free from zirconium and by the gravimetric method on steels containing zirconium.

Not all ingots were analyzed for phosphorus as the same raw material was used for all.

All ingots were analyzed for aluminum. The aluminum content of these steels comes largely from the zirconium alloys used. In I-29 the aluminum was intentionally added. In the other steels 0.005 to 0.01 per cent. aluminum was used as deoxidizer.

The zirconium, titanium and aluminum analyses were all made in duplicate by Lieutenant R. McLane, U. S. N., under the direction of the authors, and represent the average of closely agreeing duplicate determinations. The segregation of zirconium is a real phenomenon and not an analytical error.

Rolling of the Nickel-Silicon Steels

The 3 inch x 6 inch ingots were ground free from surface imperfections, cross-rolled to a little over 12 inches wide, then turned and straight-rolled lengthwise.

They were then reheated and scaled by beating with mallets, again reheated and finish-rolled to ¼ inch gage. They were then again heated, placed on a flat surface and straightened by running a heavy roller over them. The sheets were then sheared into plates, discarding the piped sheet from the top of the ingot. Three or four plates were obtained from each sheet. The plate nearest the top of the ingot was marked "A," the next "B," and so on. Rolling temperatures were taken with an optical pyrometer.

The rolling data are given in Table 20.

TABLE 20

No.	Temp. First Pass		Cross Passes	Straight Passes	Temp. Last Straight Pass		Finish Passes	Temp. after Last Finish Pass	
	° C.	° F.			° C.	° F.		° C.	° F.
I-1	1115	2040	7	5	965	1770	5	860	1580
I-2	1140	2085	7	5	955	1755	5	875	1610
I-3	1120	2050	8	5	945	1730	5	950	1745
I-4	1140	2085	7	5	965	1770	5	915	1680
I-5	1115	2035	7	5	980	1795	5	940	1720
I-6	1105	2025	7	5	965	1770	5	875	1610
I-7	1115	2035	7	5	945	1730	5	885	1625
I-8	1075	1970	8	6	900	1650	5	900	1650
I-9	1100	2015	9	5	930	1705	5	895	1640
I-10	1080	1980	9	7	915	1680	5	860	1580
I-11	1065	1950	9	7	886	1625	6	885	1625
I-12	1105	2035	9	7	925	1695	6	895	1640
I-13	1045	1915	8	7	900	1650	6	850	1560
I-14	1070	1960	9	7	925	1695	5	830	1530
I-15	1070	1960	10	6	885	1625	6	860	1580
I-16	1035	1895	10	6	930	1705	6	865	1585
I-17	1080	1980	..	..	925	1695	4	925	1695
I-18	1070	1960	..	..	900	1650	4	930	1705
I-19	1065	1950	13	6	915	1680	4	885	1625
I-20	1055	1935	11	5	930	1705	4	930	1705
I-21	1090	1995	11	7	885	1625	4	915	1680
I-22	1125	2060	10	6	875	1610	5	915	1680
I-23	1130	2070	9	6	925	1695	6	925	1695
I-24	1120	2050	..	..	955	1755	6	915	1680
I-25	1145	2095	..	..	950	1745	6	860	1580
I-26	1150	2105	12	6	935	1720	6	865	1585
I-27	1130	2070	Broke going through rolls						
I-28	1050	1925	11	7	955	1755	5	895	1640
I-29	1090	1995	14	7	905	1665	5	895	1640
I-30	1045	1915	11	7	875	1610	5	885	1625
I-31	1080	1980	11	7	860	1580	5	895	1640
I-32	1035	1895	11	7	850	1560	5	850	1565

The plates were then heat-treated.

For reasons that have no connection with the present discussion, many of the plates were drawn several times at increasing temperatures. Since

the effect of the last draw is super-imposed on that of previous draws, the effect of the previous draws cannot be wholly neglected, although the final draw chiefly determined the degree of softening. The details of the various draws will not be given, but attention is called to the column in Table 16 showing the number of draws. The Brinell hardness figures in Table 16 are averages of four determinations (made on both ends of both tensile specimens) after grinding off 0.02 inch of the surface layer.

Test Specimens and Methods of Testing Used on Nickel-Silicon Steels

From the 12 inch x 12 inch x ¼ inch plates two longitudinal and two transverse tensile specimens and two longitudinal and two transverse Izod specimens were cut with a 1/10 inch rubber bond emery wheel. Of each pair of specimens, one was taken from one corner of the plate and the other from the opposite corner.

The flat tensile specimens were ¼ inch x ½ inch x 2½ inches in the breaking section, which was filleted into the gripped portions which were about 1 inch x 1 inch x ¼ inch. The specimens were roughly cut out with the wheel, then finished by hand.

The gage length was 2 inches. Proportional limits were obtained from the stress-strain diagrams taken with a Berry strain gage.

The Izod specimens were .25 inch (the plate thickness) x .394 inch x 4 inches. The notch was .079 inch (2 mm.) deep with .039 inch (1 mm.) radius at the base of the notch (Mesnager notch). The results on materials of low impact resistance are higher with this notch than with the regular Izod notch used for the Izod tests on the steels previously described.

The notch was cut with a shaper tool since drilling this round notch was not practical on these hard steels. The notch was cut into the ¼ inch face of the specimen, the apex of the notch thus being backed up by .315 inch of metal.

The direction of impact was thus parallel to the surface of the plate.

The Izod figures have been reduced to the basis of a .394 inch x .394 inch (10 mm. x 10 mm.) standard square bar. Any deviation from the .25 inch thickness was of course taken account of in this calculation and in computing the area of the tensile specimens. The plates were very uniform in thickness and very close to gage.

Two notches were cut and two tests made on each Izod specimen. The Izod figures are the average of two determinations. The endurance specimens were ¼ inch x 1 inch x about 6 inches. (See Plate 19). These had the same free test length (.667 inch) as the round specimens used on other steels, and, like those, were necked down on a 1 inch radius. The minimum section of the neck was 1 inch x .135 inch.

Upton-Lewis endurance test bars—flats—actual size.

PLATE 19.—Shape of flat, necked, endurance specimens used on nickel-silicon steels.

The necks were ground in such a manner that the grinding scratches all ran in the direction of the applied stress. The elaborate polishing to remove transverse scratches which was required on the round specimens which were ground circumferentially, was therefore not required on these specimens. They were finished on rotating laps covered with emery cloth. The last lap to be applied was covered with well worn No. 000 garnet ("Three M-ite") cloth.

Special springs were provided for the Upton-Lewis endurance machines of suitable strength to give a cross-head amplitude small enough to be measurable with Ames dials without too much difficulty. With these larger test pieces and stiffer springs the accuracy of stress measurement was not quite so good as on the round specimens, and it was much more difficult to avoid trouble from friction in the pivots. If the pivot was too loose the end position of the dial needle at each limit of its travel was not clear. By tightening up the pivot the dial readings became satisfactory, but it was very difficult to adjust lock nuts to maintain that position.

The accuracy of the stress measurements for these flat endurance specimens was distinctly less than with the round pieces, and most of the endurance limits are probably slightly on the low side because of some pivot friction.

Appendix D.

The following pages contain a tabular summary of the available data on steels containing molybdenum, together with references to the original sources in the literature. These references are given in Appendix E.

Carbon-Molybdenum Steels

Composition C	Composition Mo	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.19– .29 .74– .81	.45– 4.50 .50– 1.98	185	...	...	...	...	...	Electrical resistance
.07– .12	.24–23.75	186	...	Yes	...	Yes	Yes	......
.06– .20	up to .30	187	...	...	...	...	...	......
.55	3.72	188	...	Yes	...	...	...	......
.19– .21 .25–1.36	1.02– 1.06 2.11– 2.50	53	...	Yes	Yes	...	Yes	......
.19–1.06 .13–1.12	4.00– 4.11 7.85– 8.17	15	...	...	...	...	...	......
.33	.96	54	...	Yes	...	...	Yes	......
.30– .36	.47– .53	135	...	Yes	...	...	Yes	......
.35– .70	.32– 1.60	146	...	...	...	...	...	Thermal conductivity
.28	.95	189	...	Yes	...	...	Yes	......
.20– .80	.50–14.60	190	...	...	...	...	...	......
.10– .50	.25– 1.00	95	Yes	...	...	...	...	......
.16	.23	103	...	Yes	...	...	Yes	......
.17– .33	.30– .80	191	...	Yes	...	...	Yes	......
.44	.30	191	...	Yes	...	...	Yes	......
.20	.70	100	...	Yes	...	...	Yes	......
.20	.94	55	...	Yes	...	Yes	Yes	Critical points
up to 1.20	6.00–15.00	192	Yes	...	...	...	...	......
up to 1.72	up to 4.00	277	Yes	...	...	...	...	Magnetic properties

Silicon-Molybdenum Steels

Composition C	Composition Mo	Si	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.45	.30–1.00	1.75	193	...	Yes	...	...	...	......

Chromium-Molybdenum Steels

C	Composition Mo	Cr	Reference to Appendix E	Use Sug-gested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.19–.32	.46– .53	.91– .95	54	...	Yes	Arnold	...	Yes	......
.10–.50	.25– .50	.80–1.00	95	Yes	...	......	...	...	......
.32	.37	.90	95	...	Yes	......	...	Yes	......
.32	**.37**	**.90**	**92**	...	**Yes**	......	...	Yes	Compression, torsion, transverse
.15–.50	.25–1.00	.70–1.10	91	...	Yes	......	...	Yes	Torsion, transverse
.50	.30	.60	274	...	Yes	......	Yes	Yes	Dimensional changes
......	.20–5.00	.20–3.00	194	Yes	...	......	...	...	......
.06–.18	Tr–1.00	Tr– .75							
.38–.55	Tr–1.00	Tr–2.00	90	...	Yes	......	...	Yes	......
.20–.35	Tr–1.00	Tr–1.20							
.13	.48	.96	123	...	...	......	...	...	Case hardening
.13–.26	.35– .36	.61– .80	105	...	Yes	......	...	Yes	Case hardening
.15–.60	.25– .50	.70–1.00	100	...	Yes	......	...	Yes	......
.15–.45	.35– .45	.80– .90	109	...	Yes	......	...	Yes	......
.23–.36	.20– .75	.70–1.00	103	...	Yes	......	...	Yes	......
.25–.40	.75–1.00	.80–1.00	15, p. 450	...	Yes	......	...	Yes	......
.27	.42	.83	101	...	Yes	......	Yes	Yes	......
.27	.52	.88	55	...	Yes	......	Yes	Yes	Critical points
.27	.50	1.00	106	...	Yes	......	...	Yes	......
.30	.35	1.02	196	...	Yes	......	...	Yes	......
.30–.45	.30– .40	.50–1.00	119	...	...	......	Yes	Yes	......
.38	.34	.86	120	...	Yes	......	...	Yes	Prop. at high temps.
.47	.35	.98	121	...	Yes	......	...	...	" " " "
.42	.09	1.04	118	...	Yes	Yes	Yes	Yes	Torsion shear tests
.28	.70	1.18	111	...	Yes	......	Yes	Yes	" " "
up to 1.20	6.00–15.00	2.50–6.00	192	Yes	...	......	...	...	......
.50–.70	2.00– 3.00	Tr	195	Yes	...	......	...	...	......
.48	.18	1.22	133	...	...	Yes	...	Yes	......
.30–.50	.18– .20	.76–1.03	47	...	Yes	Yes	...	Yes	Torsion tests
.27	.41	.99	122	...	Yes	......	...	Yes	Prop. at high temps.
.30	.15	.80	295	Yes	Yes	......	...	Yes	......
.25	.75	.75	316	Yes	...	......	...	...	......

Nickel-Molybdenum Steels

C	Composition Mo	Ni	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.15 .30	.53 .45	.98 .99	54	...	Yes	Arnold	...	Yes	......
.35–.54	.63–4.36	2.96–3.60	190	...	Yes	......	Yes	Yes	......
.40	.40	1.50	95	...	Yes	......	...	...	......
.41	.12	1.70	118	...	Yes	Yes	Yes	Yes	Torsion tests
.20–.40	.30– .70	3.00–5.00	91	...	...	......	...	Yes	......
.54	3.65	1.02	146	...	...	......	...	...	Thermal conductivity
.13	.20	1.58	105	...	Yes	......	...	...	Case hardening
.15–.25	1.00–2.00	5.00–7.00	197	Yes	...	......	...	...	Plus 0 to 3 per cent. tungsten
.30	.62	5.01	198	...	Yes	......	...	Yes	......
.30	.60	4.00	109	...	Yes	......	...	Yes	......
.19	.54	7.86	62	...	Yes	......	Yes	Yes	......
.14	.25	1.55	235	Yes	Yes	......	...	Yes	Case hardening

Nickel-Silicon-Molybdenum Steels

C	Composition Mo	Ni	Si	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.42–.44	.27–.78	3.00–3.50	1.45–1.80	66	...	Yes	...	...	Yes	......
.37	.70	2.95	2.50	199	...	Yes	...	Yes	Yes	......
.39–.66	up to .70	up to .70	up to .70	126	...	Yes	...	...	Yes	......

Vanadium-Molybdenum Steels

C	Composition Mo	V	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.30	.52	.21	54	...	Yes	Arnold	...	Yes	......
up to 1.00	6.00 up	.10–1.00	200	Yes	...	......	...	...	......

Nickel-Chromium-Molybdenum Steels

C	Composition Mo	Ni	Cr	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.34	.41	3.07	.77	95	...	Yes	...	...	Yes	......
.10–.40	.25–1.00	1.00–2.00	.45–.65							
.25	.30	2.00	.75	91	...	Yes	...	Yes	Yes	......
.35	.50	3.25	.75							
......	.25	1.00	.25	201	Yes	...	...	...	...	......
......	5.00	5.00	2.50							
.25	.60	2.00	.75	109	...	Yes	...	...	Yes	......
.35	.40	3.00	.75							
.25–.34	.43– .70	2.37–2.84	.63– .85	110	Yes	Yes	...	Yes	Yes	Critical points
.30	.53	3.05	.53	125	...	Yes	...	Yes	Yes	Co-efficient expansion
.23–.30	.30– .55	2.50–3.00	.75–1.00	100	...	Yes	...	...	Yes	......
.44	.36	2.04	.99	103	...	Yes	...	...	Yes	......
.22–.30	.30– .50	2.75–3.25	.70– .90	101	...	Yes	...	...	Yes	......
.50	.75	1.01	.74	198	...	Yes	...	...	Yes	......
.50	.75	.85	1.25	...	...	...	...	...	...	......
.60	.65	.65	1.25	128	Yes	...	...	...	...	......
.70	.50	.50	1.00							
.30–.50	Tr–1.50	3.00–5.00	.50–1.50	202	Yes	...	...	...	...	Armor plate. Also contains tr. to 50 per cent. vanadium

Nickel-Vanadium-Molybdenum Steels

C	Composition Mo	Ni	V	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.82	1.70	1.95	.48	196	Yes	...	...	...	...	......
......	.25–3.00	1.00–5.00	Tr–.60	201	Yes	...	...	...	...	......

Chromium-Vanadium-Molybdenum Steels

Composition C	Mo	Cr	V	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.39	.87	1.05	.17	...	...	...	...	...	...	......
.10–.55	.25– .50	.80–1.00	.15	95	...	Yes	...	...	Yes	......
.39	.85	1.06	.17	91	...	Yes	...	...	Yes	Torsion, transverse, compression
.28	.75	1.20	.20	...	...	...	...	...	...	......
.41	.70–1.00	1.00–1.10	.20– .45	198	...	Yes	...	...	Yes	......
.38	.80	1.00	.18	103	...	Yes	...	...	Yes	......
.35	.75–1.00	1.00	.15	193	...	Yes	...	...	Yes	......
.34–.51	.22–1.45	1.10–1.50	.16– .28	62	...	Yes	...	...	Yes	......
.40	.80	1.00	.20	109	...	Yes	...	...	Yes	......
.25–.40	.75–1.00	1.00	.15	15, p. 430	...	Yes	...	...	Yes	......

Cobalt-Chromium-Molybdenum Steels

Composition C	Mo	Cr	Co	Reference to Appendix E	Use Suggested	Data on Mechanical Properties	Repeated Load Test	Impact Test	Heat Treatment	Other Data
.65	3.05	2.16	1.33	198	...	Yes	...	...	Yes	......

Complex and Special Steels

Composition C	Mo	Ni	Cr	V	W	Si	Reference to Appendix E
.30–.60	1.25–1.50	1.50– 3.50	.30– .80	.10– .30	1.25–1.50	1.00–2.50	203
Tr–.25	1.00–2.00	5.00– 7.00	....	....	Tr– 3.00	....	197
.15–.25	.20– .50	5.00–12.00	.15– .25	.20– .50	.50– .70	....	204
.30–.60	1.00–3.00	60.00–70.00	10.00–15.00	.20–1.00	....	....	205

High Speed Steels

Composition						
C	Mo	Cr	V	Co	W	Reference to Appendix E
.50–1.00	6.00–10.00	1.00–7.00	.10–1.00	....	....	200
.70	.75	5.00	1.00	4.00	18.00	207
.50	1.56	5.04	.82	....	18.54	208
.65	8.00	4.00	1.50	5.00	....	209
.65	7.50	3.25	1.25	....	....	210
1.50	8.50	21.00	.50	....	8.50	211
up to 1.85	4.00– 6.00	1.00–2.00	....	....	....	195
.20– .75	.25– 1.00	3.00–5.00	1.10–1.50	....	12.00–18.00	203

Appendix E.

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